SMITHSONIAN

CONTRIBUTIONS TO KNOWLEDGE

VOL. XXXIV

EVERY MAN IS A VALUABLE MEMBER OF SOCIETY WHO, BY HIS OBSERVATIONS, RESEARCHES, AND EXPERIMENTS, PROCURES KNOWLEDGE FOR MEN—SMITHSON

(No. 1739)

CITY OF WASHINGTON
PUBLISHED BY THE SMITHSONIAN INSTITUTION
1907

ADVERTISEMENT.

This volume forms the thirty-fourth of a series, composed of original memoirs on different branches of knowledge, published at the expense and under the direction of the Smithsonian Institution. The publication of this series forms part of a general plan adopted for carrying into effect the benevolent intentions of JAMES SMITHSON, Esq., of England. This gentleman left his property in trust to the United States of America to found at Washington an institution which should bear his own name and have for its objects the "*increase* and *diffusion* of knowledge among men." This trust was accepted by the Government of the United States, and acts of Congress were passed August 10, 1846, and March 12, 1894, constituting the President, the Vice-President, the Chief Justice of the United States, and the heads of Executive Departments an establishment under the name of the "SMITHSONIAN INSTITUTION, FOR THE INCREASE AND DIFFUSION OF KNOWLEDGE AMONG MEN." The members of this establishment are to hold stated and special meetings for the supervision of the affairs of the Institution and for the advice and instruction of a Board of Regents to whom the financial and other affairs are intrusted.

The Board of Regents consists of two members *ex-officio* of the establishment, namely, the Vice-President of the United States and the Chief Justice of the United States, together with twelve other members, three of whom are appointed from the Senate by its President, three from the House of Representatives by the Speaker, and six persons appointed by a joint resolution of both Houses. To this board is given the power of electing a Secretary and other officers for conducting the active operations of the Institution.

To carry into effect the purposes of the testator, the plan of organization should evidently embrace two objects: one, the increase of knowledge by the addition of new truths to the existing stock; the other, the diffusion of knowledge, thus increased, among men. No restriction is made in favor of any kind of knowledge, and hence each branch is entitled to and should receive a share of attention.

The act of Congress establishing the Institution directs, as a part of the plan of organization, the formation of a library, a museum, and a gallery of art, together with provisions for physical research and popular lectures, while it leaves to the Regents the power of adopting such other parts of an organization as they may deem best suited to promote the objects of the bequest.

After much deliberation, the Regents resolved to apportion the annual income specifically among the different objects and operations of the Institution in such manner as may, in the judgment of the Regents, be necessary and proper for each, according to its intrinsic importance, and a compliance in good faith with the law.

The following are the details of the parts of the general plan of organization provisionally adopted at the meeting of the Regents December 8, 1847:

DETAILS OF THE FIRST PART OF THE PLAN.

I. To increase Knowledge. *It is proposed to stimulate research by offering rewards for original memoirs on all subjects of investigation.*

1. The memoirs thus obtained to be published in a series of volumes, in a quarto form, and entitled "Smithsonian Contributions to Knowledge."

2. No memoir on subjects of physical science to be accepted for publication which does not furnish a positive addition to human knowledge, resting on original research; and all unverified speculations to be rejected.

3. Each memoir presented to the Institution to be submitted for examination to a commission of persons of reputation for learning in the branch to which the memoir pertains, and to be accepted for publication only in case the report of this commission is favorable.

4. The commission to be chosen by the officers of the Institution, and the name of the author, as far as practicable, concealed, unless a favorable decision be made.

5. The volumes of the memoirs to be exchanged for the transactions of literary and scientific societies, and copies to be given to all the colleges and principal libraries in this country. One part of the remaining copies may be offered for sale, and the other carefully preserved to form complete sets of the work to supply the demand from new institutions.

6. An abstract, or popular account, of the contents of these memoirs to be given to the public through the annual report of the Regents to Congress.

II. To increase Knowledge.—*It is also proposed to appropriate a portion of the income annually to special objects of research, under the direction of suitable persons.*

1. The objects and the amount appropriated to be recommended by counsellors of the Institution.

2. Appropriations in different years to different objects, so that in course of time each branch of knowledge may receive a share.

3. The results obtained from these appropriations to be published, with the memoirs before mentioned, in the volumes of the Smithsonian Contributions to Knowledge.

4. Examples of objects for which appropriations may be made:

(1) System of extended meteorological observations for solving the problem of American storms.

(2) Explorations in descriptive natural history, and geological, mathematical, and topographical surveys, to collect material for the formation of a physical atlas of the United States.

(3) Solution of experimental problems, such as a new determination of the weight of the earth, of the velocity of electricity, and of light; chemical analyses of soils and plants; collection and publication of scientific facts, accumulated in the offices of Government.

(4) Institution of statistical inquiries with reference to physical, moral, and political subjects.

(5) Historical researches and accurate surveys of places celebrated in American history.

(6) Ethnological researches, particularly with reference to the different races of men in North America; also explorations and accurate surveys of the mounds and other remains of the ancient people of our country.

I. To diffuse Knowledge.—*It is proposed to publish a series of reports, giving an account of the new discoveries in science, and of the changes made from year to year in all branches of knowledge not strictly professional.*

1. Some of these reports may be published annually, others at longer intervals, as the income of the Institution or the changes in the branches of knowledge may indicate.

2. The reports are to be prepared by collaborators eminent in the different branches of knowledge.

3. Each collaborator to be furnished with the journals and publications, domestic and foreign, necessary to the compilation of his report; to be paid a certain sum for his labors, and to be named on the title-page of the report.

4. The reports to be published in separate parts, so that persons interested in a particular branch can procure the parts relating to it without purchasing the whole.

5. These reports may be presented to Congress for partial distribution, the remaining copies to be given to literary and scientific institutions and sold to individuals for a moderate price.

The following are some of the subjects which may be embraced in the reports:

I. PHYSICAL CLASS.

1. Physics, including astronomy, natural philosophy, chemistry, and meteorology.
2. Natural history, including botany, zoology, geology, etc.
3. Agriculture.
4. Application of science to arts.

II. MORAL AND POLITICAL CLASS.

5. Ethnology, including particular history, comparative philology, antiquities, etc.
6. Statistics and political economy.
7. Mental and moral philosophy.
8. A survey of the political events of the world; penal reform, etc.

III. LITERATURE AND THE FINE ARTS.

9. Modern literature.
10. The fine arts, and their application to the useful arts.
11. Bibliography.
12. Obituary notices of distinguished individuals.

II. To diffuse Knowledge.—*It is proposed to publish occasionally separate treatises on subjects of general interest.*

1. These treatises may occasionally consist of valuable memoirs translated from foreign languages, or of articles prepared under the direction of the Institution, or procured by offering premiums for the best exposition of a given subject.

2. The treatises to be submitted to a commission of competent judges previous to their publication.

DETAILS OF THE SECOND PART OF THE PLAN OF ORGANIZATION.

This part contemplates the formation of a library, a museum, and a gallery of art.

1. To carry out the plan before described a library will be required consisting, first, of a complete collection of the transactions and proceedings of all the learned societies of the world; second, of the more important current periodical publications and other works necessary in preparing the periodical reports.

2. The Institution should make special collections particularly of objects to illustrate and verify its own publications; also a collection of instruments of research in all branches of experimental science.

3. With reference to the collection of books other than those mentioned above, catalogues of all the different libraries in the United States should be procured, in order that the valuable books first purchased may be such as are not to be found elsewhere in the United States.

4. Also catalogues of memoirs and of books in foreign libraries and other materials should be collected, for rendering the Institution a center of bibliographical knowledge, whence the student may be directed to any work which he may require.

5. It is believed that the collections in natural history will increase by donation as rapidly as the income of the Institution can make provision for their reception, and therefore it will seldom be necessary to purchase any article of this kind.

6. Attempts should be made to procure for the gallery of art casts of the most celebrated articles of ancient and modern sculpture.

7. The arts may be encouraged by providing a room, free of expense, for the exhibition of the objects of the Art Union and other similar societies.

8. A small appropriation should annually be made for models of antiquities, such as those of the remains of ancient temples, etc.

9. The Secretary and his assistants, during the session of Congress, will be required to illustrate new discoveries in science and to exhibit new objects of art. Distinguished individuals should also be invited to give lectures on subjects of general interest.

In accordance with the rules adopted in the programme of organization, each memoir in this volume has been favorably reported on by a commission appointed for its examination. It is, however, impossible, in most cases, to verify the statements of an author, and therefore neither the commission nor the Institution can be responsible for more than the general character of a memoir.

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SMITHSONIAN CONTRIBUTIONS TO KNOWLEDGE

PART OF VOLUME XXXIV

A COMPARISON OF THE FEATURES OF THE EARTH AND THE MOON

BY

N. S. SHALER

PROFESSOR, HARVARD UNIVERSITY

(No. 1438)

CITY OF WASHINGTON

PUBLISHED BY THE SMITHSONIAN INSTITUTION

1903

The Knickerbocker Press, New York

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1903

Commission to whom this memoir has been referred :

GEORGE P. MERRILL,

C. G. ABBOT.

ADVERTISEMENT.

For more than twelve years past I have been preparing the material for the publication of a work, on the part of the Smithsonian Institution, which it was hoped would consist essentially of photographic views of the moon, so complete and, it was expected (with the advance of photography), so minute, that the features of our satellite might be studied in them by the geologist and the selenographer, nearly as well as by the astronomer at the telescope. This hope has only been partially fulfilled, for photography, which has made such eminent advances in the reproduction of nebulæ and like celestial features, has indeed progressed in lunar work, but not to the same extent as in other fields. The expectation that such a complete work could be advantageously published for this purpose has, then, been laid aside for the present.

It has been decided to draw from the material prepared for this larger work, some photographs taken at the Lick Observatory and the Paris Observatory, and particularly some recently obtained by Professor Ritchey at the Yerkes Observatory, for which I have to express the thanks of the Institution. These illustrations are attached to the present paper by Professor Shaler, and may, then, be considered to be a separate contribution by the Institution to the study of selenography.

Professor Shaler's memoir gives the results of personal studies carried on for a third of a century. He has devoted about one hundred nights to telescopic study of the moon with the Mertz equatorial of Harvard College Observatory, his later researches having been chiefly by means of photographs at Harvard University, with which he has so long been connected.

In accordance with the rule adopted by the Smithsonian Institution, the memoir has been submitted for examination to a committee consisting of Dr. George P. Merrill, Head Curator of Geology in the U. S. National Museum, and Mr. C. G. Abbot of the Smithsonian Astrophysical Observatory.

S. P. LANGLEY,

SECRETARY.

Smithsonian Institution,

Washington, December, 1903.

LIST OF PLATES.

A COMPARISON OF THE FEATURES OF THE EARTH AND THE MOON.

By N. S. Shaler.

PRELIMINARY NOTE.

The object of this paper is to set forth the general results of certain studies concerning the form and structure of the lunar surface with reference to various terrestrial problems.

These studies were begun in 1867 with the Mertz equatorial of the Harvard College Observatory, at the time when my lamented friend and colleague, Joseph Winlock, was director, and have been continued in a desultory manner, from time to time, for a third of a century. Between 1867 and 1872 about one hundred nights were devoted to telescopic work; since that time what has been done has been almost altogether by means of photographs, which have of recent years become much more convenient and for my purpose more serviceable than the opportunities afforded by an instrument even if it were as good as the Harvard Mertz.

It should be observed that so far as possible my task has been kept apart from problems of selenology or selenography strictly so called. The ends sought have been those alone which had distinct reference to geology. Certain questions, as, for instance, that concerning the antiquity of the lunar surface, necessarily touch upon matters which relate to the history of the moon as an individual sphere. In fact almost all the questions brought up by studies on the satellite are more or less entangled with those relating to the evolution of the planet, so that except for the detailed account of the features of either body they must needs be considered together. These features may be compared by types, and in the main the following essay consists of such comparisons.

If other duties permit I hope to present the matters discussed in the following pages in a more extended form, one in which it will be possible to illustrate the facts here set forth, as well as to discuss the conclusions attained in an ampler manner. Almost all the points I have endeavored to make clear demand this more extended treatment. As many of them are debatable, some of them, indeed, requiring more observations and comparisons than I have been able to give, I may hope that the criticism this paper may receive will enable me to better the work which it describes.

GENERAL DESCRIPTION OF THE MOON.

Although the moon has been the most studied of all celestial objects, few persons, except astronomers, have a clear idea of even the general results which have been derived from the vast body of observations that have been made upon it. On this account it appears desirable to preface the account of the special inquiries which are set forth in the following pages by a statement of what is known concerning this nearest neighbor of our earth. This account will necessarily be limited to the facts which can be set forth in other than mathematical form ; fortunately, these include all that the reader needs to have in mind in order to obtain a fairly clear understanding of the questions which are to be discussed.

The history of primitive astronomy shows that the moon, of all celestial objects, from the beginning of man's intellectual development has been the most closely observed. Although the sun was doubtless recognized by the lowliest man as the most important feature of the heavens, as the giver of life, the conditions under which it is seen, especially its blinding light, long made any extended study of it impossible. So, except for the very evident changes of its course across the sky and the consequent succession of the seasons, little was known of the solar center two hundred years ago, and, save its approximate distance from the earth, its mass, and its general relations to the planets, not much knowledge was gained until the last century. On the other hand, the moon, because of its nearness, being only about one four-hundredth part as remote from the earth as the sun, has in a noteworthy way entered into the records of men. Its relatively short period of change and the very pronounced character of its alterations made it the first index of time beyond the round of the day. It is evident, indeed, that as soon as men began to reckon time they used the lunar month to make their tally, rather than that of the solar year. Moreover, the surface of the moon reveals much to the naked eye, not clearly, but sufficiently well to afford the basis for speculation and to tempt the imagination to create there a world like our own. It is therefore not surprising that a host of myths concerning the nature of our satellite grew up in the days before the telescope. It is interesting to note the fact that many of these myths have not only become fixed in the minds of uninstructed people, but they have had a remarkable influence upon the minds of modern astronomers, limiting their capacity to interpret what their instruments clearly reveal to them. At every stage in the advance of selenography we note the curious persistency of the endeavor not only to interpret the lunar features by the terrestrial, but to warp the observed facts into accord with those seen on the earth. There is perhaps no better instance of the extent to which prepossessions and prejudices may affect the judgment of the most conscientious observer, blinding him to evident truth, than the history of lunar inquiries affords.

The story of the physical conditions of the moon had best be begun by noting that the relation of our satellite to a larger sphere is not exceptional, but the most characteristic of all the relations of one stellar body to another. Of the planets in the solar system, all save the two nearest to the sun, Mercury and Venus, have one or more smaller spheres circling about them. The relation of the sun to the several planets in a larger way repeats this plan of grouping lesser about greater orbs.

It is generally believed by astronomers that the celestial spheres have been formed by a process of condensation, due to gravitation, of matter which was originally widely diffused; that our solar system, before it was organized into the sun and lesser bodies, was in the form of a diffused nebulous mass of spheroidal form which extended beyond the orbit of the outermost planet. As this matter gathered towards the center, the material now in each of the planets and its satellites parted from the parent body, probably at first in the form of a nebulous ring, or spiral, which in time broke and gathered into a spheroidal mass. In that detached portion of the parent nebula the process of concentration was repeated, with the result that satellites, or, as we may term them, secondary planets, were formed substantially as the greater spheres were set off from the sun. There are many questions and doubts concerning the details of this nebular theory, but that the evolution of our solar system and probably of all stellar systems took place in substantially the manner indicated appears to be eminently probable; it is, indeed, fairly well established by what we know of the distant nebulæ and by the rings of Saturn, which apparently contain the material which normally should have formed one or more of its satellites, but which for some unknown reason have remained unbroken.

It is not certain at just what stage in the concentration of a nebula a planet or a satellite may be set off from the parent body; nor can the present distance of the satellite from the main sphere be assumed as that at which the parting took place. It is possible that the concentration of the parent body had gone so far that the diffused or nebulous stage of its materials had been passed by and the more advanced stage of igneous fluidity entered on. It is, however, more likely that in all cases the separation occurred while the particles of matter were divided as they are in a gas or vapor. As soon as the two spheres are separated from one another, and so long as they remain in any measure fluid, the difference in their gravitative attraction on the nearer and more remote part of their masses induces tides, and the effect of these tidal movements, as has been shown by Professor George Darwin, is necessarily to impel the two bodies farther apart. It seems certain that before the earth and the moon became essentially rigid, as they now are, the effect of these tides in driving them apart must have been great enough to account for a considerable part of the interval which now separates them.

In the present condition of the moon, it is a sphere having a computed diameter of 2159.6 miles and its mean distance from the earth 238,818 miles. So far as has been determined, the moon exhibits no trace of flattening at the poles such as characterizes the earth, unless, as is possible, there are irregularities of figure on the unseen part of the sphere. It is essentially globular in form. The fact that the moon is not flattened at its poles probably indicates that if it once rotated in the manner of the planet it ceased to do so before it became solid.

The measure of density of the moon—*i. e.*, the proportion of its weight to its bulk—is only about six-tenths that of the earth. While the earth's mean density is nearly 5.7 times that of water, that of the moon is about 3.5 times as great. Thus the total gravitative force of the lunar mass is to be reckoned as only about $\frac{1}{81}$ that of our planet.

As the moon revolves on its polar axis but once in about a month, and at a rate that tends to keep the same part of its surface turned towards the earth, we should, but for the phenomenon of librations, see no more than one-half of its superficial area. Owing, however, to this feature, which is due to certain complications of the moon's exceedingly varied movements, the satellite in effect sways in relation to the earth so that at certain times we see farther to the east and at others farther to the west of its center, and in the succession of these movements we are able to behold somewhat more than one-half the total area, in fact about six-tenths of it. It is impossible to set forth in this writing the reasons for the librations of the moon, as the matter cannot be explained without giving in mathematical form a full account of the motion of our satellite, which is one of the most complicated of astronomical problems. An excellent non-mathematical presentation of the question, which affords a sufficient idea of it, may be found in *The Moon*, by Richard A. Proctor, pp. 117 *et seq.*, D. Appleton & Co., New York, 1878.

As noted below, there is some accessible information going to show that even beyond the extreme field revealed by the librations the surface of the moon has the same character as that which is visible. Thus we find that up to the limits of the visible part there is no sign of change in the nature of the surface. It is therefore reasonable to conclude that the same characteristics extend for some distance beyond the limits of vision. We also note on the verge of the unseen field the hither margins of certain ring-shaped structures, evidently of large size, the so-called volcanoes, so that it is fair to conclude that these features are continued on the unseen part. Moreover, there are some light-colored bands, such as on this side of the moon always radiate from crater-like pits, which apparently come over from such centers on the unseen part. These several facts, taken together, make it eminently probable that the unseen four-tenths of the lunar surface in no essential way differs from that we observe. It is, indeed, altogether likely that we see every type of structure that exists on the moon, and that a view of its whole area would add nothing essentially new to our knowledge of the sphere.

Seen by persons of ordinarily good vision, even at a distance of about 240,000 miles, the moon reveals much of its surface shape, structure, and color; it is evident that the color varies greatly from very bright areas to those which are relatively dark, that the latter are somewhat less in total extent than the former and that they are disposed in a general way across the northern hemisphere.[1] (See plates I. to VII. inclusive.) Persons of more than usually good vision may, under favorable conditions, see on the edge of the illuminated area the ragged line of the sunlight, which indicates that the surface is very irregular, the high points coming into the day before the lower are illuminated. Such persons at time of full moon can also note, though faintly, some of the bright bands which, radiating from certain crater-like pits, extend for great distances over the surface. So, too, they may see at the first stage of the new and the last of the old moon, the light from the sunlit earth slightly illuminating the dark part of the lunar sphere, or, as it is often termed, the old moon in the arms of the new.

With the best modern telescopes under the most suitable conditions of observation, the moon is seen as it would be by the unaided eye if it were not more than about forty miles from the observer. The conditions of this seeing are much more favorable than those under which we behold a range of terrestrial mountains at that distance, for the reason that the air, and especially the moisture, in our atmosphere hinders and confuses the light, and there is several times as much of this obstruction encountered in a distance of forty miles along the earth's surface as there is in looking vertically upwards.

Seen with the greater telescopes, the surface of the moon may reveal to able observers, in the rare moments of the best seeing, circular objects, such as pits, which are perhaps not more than five hundred feet in diameter. Elevations of much less height may be detected by their shadows, which, because there is no trace of an atmosphere on the moon, are extraordinarily sharp, the line between the dark and light being as distinct as though drawn by a ruler. Elongate objects, such as rifts or crevices in the surface, because of their length, may be visible even when they are only a few score feet in width, for the same reason that while a black dot on a wall may not make any impression on the eye, a line no wider than the dot can be readily perceived. Owing to these conditions, the surface of the moon has revealed many of its features to us, perhaps about as well as we could discern them by the naked eye if the sphere were no more than twenty miles away.

Separated from all theories and prepossessions, the most important points which have been ascertained as to the condition of the moon's surface are as follows:

The surface differs from that of the earth in the fact that it lacks the envelopes of air and water. That there is no air is indicated by the feature above noted, that there is no diffusion of the sunlight, the shadows being absolutely black and with perfectly clean-cut edges. It is also shown by the fact that when a star is occulted or shut out by the disc of the moon it disappears suddenly without its light being displaced, as it would be by refraction if there were any sensible

[1] It is well to note the fact that in a celestial telescope objects are seen in reverse position, or "upside down." For convenience they are usually so depicted on maps and pictures of the moon; the north pole at the bottom, and the east where it is customary to place the west on terrestrial maps.

amount of air in the line of its rays. This evidence affords proof that if there is any air at all on the moon's surface it is probably less in amount than remains in the nearest approach to a vacuum we can produce by means of an air-pump. Like proof of the airless nature of the moon is afforded by the spectroscope applied to the study of the light of an occulting star or that of the sun as it is becoming eclipsed by the moon. In fact a great body of evidence goes to show that there is no air whatever on the lunar surface.

The evidence of lack of water at the present time on the surface of the moon appears to be as complete as that which shows the lack of an atmosphere. In the first place, there are evidently no seas or even lakes of discernible size. There are clearly no rivers. If such features existed, the reflection of the sun from their surfaces would make them exceedingly conspicuous on the dark background of the moon, which for all its apparent brightness is really as dark as the more somber-hued rocks of the earth's surface when lit by the sun. Moreover, even were water present, without an atmosphere there could be no such circulation as takes place on the earth, upward to clouds and thence downward by the rain and streams to the ocean. Clouds cannot exist unless there be an atmosphere in which they can float, and even if there be an air of exceeding tenuity on the moon, it is surely insufficient to support a trace of clouds. Some distinguished astronomers have thought to discern something floating of a cloud-like nature, but these observations, though exceedingly interesting, are not sufficiently verified to have much weight against the body of well-observed facts that shows the moon to be essentially waterless.

The well-established absence of both air and water in any such quantities as are necessary to maintain organic life appears to exclude the possibility of there being any such life as that of plants and animals on the lunar surface. The reader will find below a further discussion of this question, and it may therefore here be passed with the statement that very few astronomers are now inclined to believe that the moon can possibly be the abode of living forms.

Being without an effective atmosphere, for the possible but unproved remnant that may exist there would be quite ineffective, the moon lacks the defense against radiation of heat which the air affords the earth. Therefore in the long lunar night the outflow of heat must bring the temperature of the darkened part to near that of the celestial spaces, certainly to some hundred degrees below Fahrenheit zero. Even in the long day this lack of air and consequent easy radiation must prevent any considerable warming of the surface. The temperature of the moon has been made the matter of numerous experiments. These, for various reasons, have not proved very effective. The most trustworthy, the series undertaken by S. P. Langley, indicate that at no time does the heat attain to that of melting ice.

Turning now to the shape and structure of the moon's crust, we observe that it differs much from that of the earth. Considering first the more general features, we note that there are none of those broad ridges and furrows,—the continents and the sea basins. A portion of the surface, mainly in the northern hemisphere, is occupied by broad plains which in their general shape are more nearly level than any equally extensive areas of the land, or, so far as we know, of the ocean floor of the earth, though they are beset with very many slight irregularities. These areas of rough, dark-hued plains are the seas or *maria* of selenographers, so termed because of old they were, from their relatively level nature, supposed to be areas of water. These maria occupy about one-third of the visible surface. Their height is somewhat less than that of the crust outside of their area. The remaining portion of the moon is extremely rugged. It is evident that the average declivity of the slopes is far greater than on the earth. This is apparent in all the features made visible by the telescope, and it likely extends to others too minute to be seen by the most powerful instruments. Zöllner, by a very ingenious computation based on the amount of sunlight reflected, estimates that the average angle of the lunar surface to its horizon is fifty-two degrees. Though we have no such basis for reckoning the average slope of the lands and sea bottoms of the earth, it is eminently probable that it does not amount to more than a tenth of that declivity. This difference, as well as many others, is probably due to the lack on the moon of the work of water, which so effectively breaks down the steeps of the earth, tending ever to bring the surface to a uniform level.

The most notable feature on the lunar surface is the existence of exceedingly numerous pits, generally with ring-like walls about them, which slope very steeply to a central cavity and more gently towards the surrounding country. These pits vary greatly in size; the largest are more than a hundred miles in diameter, while the smallest discernible are less than a half-mile across. The number increases as the size diminishes; there are many thousands of them, so small that they are revealed only when sought for with the most powerful telescopes and with the best seeing. In all these pits, except those of the smallest size, and possibly in these also, there is within the ring-wall and at a considerable though variable depth below its summit a nearly flat floor, which often has a central pit of small size or in its place a steep rude cone. When this plain is more than twenty miles in diameter, and with increasing numbers as the floor is wider, there are generally other irregularly scattered pits and cones. Thus in the case of Plato, a ring about sixty miles in diameter, there are some scores of these lesser pits. On the interior of the ring-walls of the pits over ten miles in diameter there are usually more or less distinct terraces, which suggest, if they do not clearly indicate, that the material now forming the solid floors they enclose was once fluid and stood at greater heights in the pit than that at which it became permanently frozen. It is, indeed, tolerably certain that the last movement of this material of the floors was one of interrupted subsidence from an originally greater elevation on the outside of the ring-wall, which is commonly of irregular height with many peaks. There are sometimes tongues or protrusions of the substance which forms the ring, as if it had flowed a short distance and then had cooled with steep slopes.

The foregoing account of the pits on the lunar surface suggests to the reader that these features are volcanoes. That view of their nature was taken by the astronomers who first saw them with the telescope and has been generally held by their successors. That they are in some way, and rather nearly, related to the volcanic vents of the earth appears certain. The nature of this relation is discussed below. We have now to note the following peculiar conditions of these pits. First, that they exist in varying proportion, with no evident law of distribution, all over the visible area of the moon. Next, that in many instances they intersect each other, showing that they were not all formed at the same time but in succession; that the larger of them are not found on the maria but on the upland and apparently the older parts of the surface; and that the evidence from the intersections clearly shows that the greater of these structures are prevailingly the elder and that in general the smallest were the latest formed. In other words, whatever was the nature of the action involved in the production of these curious structures, its energy diminished with time, until in the end it could no longer break the crust.

All over the surface of the moon, outside of the maria, in the regions not occupied by the volcano-like structures, we find an exceedingly irregular surface, consisting usually of rude excrescences with no distinct arrangement, which may attain the height of many thousand feet. These, when large, have been termed mountains, though they are very unlike any on the earth in their lack of the features due to erosion, as well as in the general absence of order in their association. Elevations of this steep, lumpy form are common on all parts of the moon. Outside of the maria they are seen at their best in the region near the north pole, where a large field thus beset is termed the Alps. From the largest of these elevations a series of like forms can be made of smaller and smaller size until they become too minute to be revealed by the telescope; as they decrease in height they tend to become more regular in shape, very often taking on a dome-like aspect. The only terrestrial elevations at all resembling these lunar reliefs are certain rarely occurring masses of trachytic lava, which appear to have been spewed out through crevices in a semi-fluid state, and to have been so rapidly hardened in cooling that the slopes of the solidified rock remained very steep. As noted in more detail below, the only reliefs on the moon's surface that remind the geologist of true mountains are certain low ridges on the surfaces of the maria.

The surface of the moon exhibits a very great number of fissures or rents, which when widely open are termed valleys, and when narrow, rills. Both these names were given because these grooves were supposed to have been the result of erosion due to flowing water. The valleys are frequently broad, in the case of that known as the Alpine valley, at certain places several miles in width: they are steep-walled and sometimes a mile or more in depth; their bottoms, when distinctly visible, are seen to be beset with crater-like pits, and show in no instance a trace of water work which necessarily excavates smooth descending floors such as we find in terrestrial valleys. The rills are narrow crevices, often so narrow that their bottoms cannot be seen; they frequently branch and in some instances are continued as branching cracks for a hundred miles or more. The characteristic rills are far more abundant than the valleys, there being many scores already described; the slighter are evidently the more numerous; a catalogue of those visible in the best telescopes would probably amount to several thousand. (See plates XII, XXI, and XXII.)

It is a noteworthy fact that in the case of the rills and in great measure also in the valleys the two sides of the fissure correspond so that if brought together the rent would be closed. This indicates that they are essentially cracks which have opened by their walls drawing apart. Curiously enough, as compared with rents in the earth's crust there is little trace of a change of level of the two sides of these rills—only in one instance is there such a displacement well made out, that known as the Strait Wall, where one side of the break is several hundred feet above the other. (See plate XXI.)

In the region outside of the maria much of the general surface of the moon between the numerous crater-like openings appears in the best seeing with powerful telescopes to be beset with minute pits, often so close together that their limits are so far confused that it appears as honeycombed, or rather as a mass of furnace slag full of holes if greatly magnified, through which the gases developed in melting the mass escaped. (See plates IX, XIII.)

Perhaps the most exceptional feature of the lunar surface, as compared with that of the earth, is found in the numerous systems of radiating light bands, in all about thirty in number, which diverge from patches of the same hue about certain of the crater-like pits. These bands of light-colored material are generally narrow, not more than a few miles in width; they extend for great distances, certain of them being over a thousand miles in length, one of them attaining to one thousand seven hundred miles in linear extent. In one instance at least, in the crater named Saussure, a band which intersects the pit may be seen crossing its floor, and less distinctly, yet clearly enough, it appears on the steep inside walls of the cavity. In no well-observed case do these radiating streaks of light-colored material coincide with the before-mentioned splits or rifts. Yet the assemblage of facts, though the observations and the theories based upon them are very discrepant, lead us to believe that they are in the nature of stains or sheets of matter on the surface of the sphere, or perhaps in the mass of the crust. At some points the rays of one system cross those of another in a manner that indicates that the one is of later formation than the other. (See plates VI, XVI, and XIX.)

Perhaps the most puzzling feature of the radiating streaks, where everything is perplexing, is found in the way they come into view and disappear in each lunar period. When the surface is illuminated by the very oblique rays of the sun they are quite invisible; as the lunar day advances they become faintly discernible, but are only seen in perfect clearness near the full moon. The reason for this peculiar appearance of these light bands under a high sun has been a matter of much conjecture; it is the subject of discussion in a later chapter of this memoir, where it is shown that inasmuch as these bands appear when the earth light falls upon the moon at a high angle, the effect must be due to the angle of incidence of the rays on the shining surfaces. It should be noted that the light bands in most instances diverge from more or less broad fields of light color about the crater-like pits, fields which have the same habit of glowing under a high illumination ; in fact, a large part of the surface of the moon, perhaps near one-tenth of its visible area, becomes thus brilliant at full moon, though it lacks that quality at the earlier and later stages of the lunar day.

In the above considered statement concerning the visible phenomena of the moon no account is taken of a great variety of obscure features which, though easily seen with fairly good instruments, have received slight attention from selenographers. As can readily be imagined, observers find it difficult to discern obscure features which cannot be classed in any group of terrestrial objects. Whosoever will narrowly inspect any part of the lunar surface, noting everything that meets his eye, will find that he observes much that cannot be explained by what is seen on the earth. It is evident, indeed, that while in the earlier stages of development this satellite in good part followed the series of changes undergone by its planet, there came a stage in which it ceased to continue the process of evolution that the parent body has undergone ; the reason for this arrest in development appears to have been the essential if not complete absence of an atmosphere and of water.

The difference in height between the lowest and highest points on the lunar surface is not determined. To the most accented reliefs, those of the higher crater walls, elevations of more than twenty-five thousand feet have been assigned ; it is, however, to be noted that all these determinations are made from the length of the shadows cast by the eminences, with no effective means of correcting for certain errors incidental to this method. It may be assumed as tolerably certain that a number of these elevations have their summits at least twenty thousand feet above their bases and that a few are yet higher. We do not know how much lower than the ground about these elevations are the lowest parts of the moon. My own observations incline me to the opinion that the difference may well amount to as much as ten thousand feet, so that the total relief of the moon may amount to somewhere between thirty and forty thousand feet. That of the earth from the deepest part of the oceans to the highest mountain summits is probably between fifty-five and sixty thousand feet ; so that notwithstanding the lack of erosion and sedimentation which in the earth continually tends to diminish the difference between the sea-floor and land areas, the surface of the satellite has a much less range of elevation than the planet. If the forces which have built the mountains and continents of the earth had operated without the erosive action of water there is little doubt that the difference in height between the highest and lowest parts would now be many times as great as it is on the moon.

AGE OF THE EXISTING LUNAR SURFACE.

Several of the most important problems to be considered in this writing intimately depend on a determination of the age of the moon's surface. If we accept the commonly adopted view as to the nature of the prevailing topographical features of that sphere and regard them as essentially volcanic, *i. e.*, as due mainly to the expulsion of heated vapors or gases from the interior of the sphere, we have a basis on which to found a determination of that age sufficiently accurate to serve our immediate purpose.

It appears eminently probable that the lunar surface must have attained to something like its present condition long before the earth came to the state in which its igneously fluid mass was crusted over. And this for the following reasons: At the time when the material of the moon and earth separated from the previously united mass we have to believe that the amount of heat they severally contained was in general proportionate to the mass of each body. Now the mass of the moon is to that of the earth as one to eighty, and its diameter about as one to four. From this, by the well-known law of cooling bodies, it follows that the moon must have acquired a permanent rigid crust, if indeed it did not become entirely frozen, long before the earth ceased to have a molten surface. There are too many doubtful elements in the computation to make any seemingly accurate reckoning trustworthy, but it appears altogether likely that the moon cooled far beyond the point where volcanic action was possible ages before the earth's surface could have frozen or perhaps have passed from the gaseous to the fluid state.

At present all the volcanic action of the earth is apparently limited to the sea-floor or regions within three hundred miles of the shore; effectively to regions where the central heat is brought upwards into strata containing water laid in them when they were deposited; the rise of the heat being due to the slow conductivity of the imposed beds. There is reason to believe that since the earliest recorded ages the earth has mainly, if not altogether, depended on such action for the volcanic outbreaks which have occurred upon it. While there may in this particular matter be some reason for doubt, there is none as to the fact that if the so-called lunar volcanoes are due to the central heat of that sphere, they must have been shaped before the crust of the earth was formed, or long before the earliest geological records. It has, however, been suggested by G. K. Gilbert[1] and others that what appear to be volcanoes on the moon are not really such, but are, in effect, punctures caused by the falling of large meteorites or bolides. This interesting suggestion commends itself at first sight as a possible explanation of the pits on the moon, structures which differ in many regards from those due to terrestrial volcanic action, in that they are often of much greater diameter, have relatively much smaller encircling cones, and show little, if any, clear evidence of lava flows, or ash showers, proceeding from them. As I propose further on in this paper to discuss the question of their nature in more detail, I shall now give only in brief the reasons why, as it seems to me, the hypothesis that they were caused by bodies falling from the sky is not verified.

It is to be noted that these so-called volcanoes of the moon, vulcanoids, as I shall term them, have generally very steep walls around their crater-like pits;

[1] See *Bull. Phil. Soc. of Washington*, vol. 12, p. 241, *et seq.*

the average outer slope, according to my estimates, exceeding forty degrees, the inner slope being generally somewhat steeper. On this hypothesis this inner slope must mark the path of the impinging bolide, and the cone that surrounds it be the result of the outthrusting action of that body, such as we note when a pebble is thrown into soft clay or a shot from a cannon enters an armor plate. We have under Gilbert's hypothesis to suppose that the impinging bodies came into contact with the moon at something like planetary velocity. Such bodies having a diameter of even a mile—and some of them must, on this hypothesis, have been of fifty or more miles diameter—would, by the conversion of their momentum into heat, have served to melt a wide field of the crust about their points of contact.[1] As there is no trace of any such bolides in the bottoms of these craters, but commonly a floor, as of hardened lava, we have to suppose that they penetrated to a great depth and that the lava flowed up after their entrance. But the necessary effect of the entrance of a mass sufficiently large to have punctured these openings would, if they had penetrated to a molten zone, have been to send up a quantity of lava far more than sufficient to fill the opening they made, while in fact with few, if any, exceptions, this lava appears at no time to have risen to the general level of the surrounding rampart. Furthermore, if the cones about the craters were due to outthrusts caused by such impacts on material stiff enough to maintain the steep walls of the crater, then we should have evidence of radial cracking in the form of open rents, such as would inevitably be developed under the assumed conditions, but have evidently not produced in far the greater number of the vulcanoids.

There is another and, taken alone, conclusive argument against the supposition that the lunar craters are due to the impact of bolides; this is found in the facts presented in the series which may be traced in the sizes and distribution of the fractures which it seeks to explain. As regards their sizes, the pits grade from the smallest that can be discerned by the most powerful telescope, probably not over five hundred feet in diameter, to rings that are one hundred miles across. The steepness of the inner slopes of these cavities does not perceptibly differ, nor is there more evidence of lava having been poured out from the larger than from the smaller craters. Moreover, there is no better evidence of radiating fractures in the case of the larger than in the smaller pits. Furthermore, there is no such relation in the masses of material composing the enveloping cones or rings as we would expect to find if they were due to the impact of bodies varying in size as we have to suppose. In many instances the walls of a pit scores of miles in diameter are no thicker or higher than in the case of other pits less than a mile across.

As regards their distribution, the craters of the moon are generally placed in such apparent lack of order as to give some warrant for the hypothesis that

[1] Assuming that the impinging body came upon the surface of the moon at planetary velocity, and that all the resulting heat was applied to its mass, the resulting temperature would exceed, according to my reckoning, 150,000 degrees. A bolide fifty miles in diameter would be likely to melt an area many times its diameter.

they must owe their origin to other than volcanic action, for on the earth we find volcanoes very generally disposed along lines which, in most if not all cases, appear to be determined by faults. In many instances, however, the lunar vulcanoids have a linear arrangement.

The vulcanoids of larger size which are arranged in linear order are not numerous. Among these may be cited the train extending from Herschel through Ptolemæus, and Alphonsus to Arzachel; that from Thibet to Stofler; that from Atlas to Franklin; and that from Vendalinus to Casatus, near the limb in the third quadrant. (See plates I and XXI.) In all these instances there are four or more pits in fairly true alignment: in alignment and in number they appear to exclude the supposition that their order is due to chance. Passing from the examples in which the greater vulcanoids are grouped in trains and taking the pits of smaller size, we find the instances of such arrangement becoming more numerous as the structures are of smaller diameter. It is, however, in but few of the pits over ten miles in diameter that there are more than three or four so placed in relation to one another that they can be said to be linearly arranged.

When, in following down the series of vulcanoids as regards size, we come to the pits less than a mile in diameter, those commonly termed craterlets, we note that the linear order, hitherto exceptional, becomes so common that the exceptions are rather to be found in the departures from it. The observations of W. H. Pickering and others, as will be noted below, make it evident that there is a causal relation between the smaller visible pits and the cracks that form on the surface of the moon. There can be no question that there are thousands of these smaller of the craterlets which are thus disposed in lines, some of the series extending for hundreds of miles. (See plate XX.)

It may be taken as evident, that in the time when the larger vulcanoids were in process of formation the conditions of strain in the moon's crust were not such as to determine that the points of outbreak should to any great extent be linearly arranged and that when thus arranged they tended to follow the meridians, rather than the parallels. In the later stages of the surface when the smaller openings were made they obviously tended to a linear order, but the direction of the lines was exceedingly varied, some of them being radially disposed with the greater vulcanoids as centers, others along lines of weakness which lie in extremely diverse positions.

Reckoning great and small, there are some hundreds of these lines of pits, a number sufficient to make it evident that they cannot be accounted for by chance. It is evident that to explain this linear order of vulcanoids by the hypothesis we are considering is difficult if not impossible, for that would require us to suppose the bolides to have been thus arranged during their movements through space. It is also to be noted that in very many instances there are pits within the larger cavities so centrally placed that they cannot be explained by the chance in-falling of bolides. Therefore, while the relation of lunar volcanoes to those of the earth is a perplexing question, there seem on the face of the facts to be sufficient reasons for rejecting the suggestion that they are due to the impact of falling bodies.

In addition to the features of the lunar volcanoes there is another though more remote reason why such falls of celestial bodies on the moon's surface have not occurred. Of these we may here mention two; these are as follows: It is evident that these vulcanoids were formed at successive times, and under somewhat diverse conditions. So far as I have been able to determine, the largest were, at least in a general way, first produced, and the smaller, approximately, in the order of diminishing size, the smallest in most instances being formed last. Now, as will be more particularly noted hereafter, the light bands which radiate from certain craters and which are clearly mere strips of material which at full moon reflect the sun's light more intensely than the general surface have evidently not been covered by deposits of ordinary meteoric matter, such as falls on the earth in considerable quantity. It thus appears that for some reason the moon, provided its surface has anything like the antiquity it appears necessary to assign to it, has not been the seat of such deposits; for the accumulation of a small amount of meteoric matter would mask such stains. We would thus, according to the Gilbert hypothesis, have to suppose a succession of showers, each sending bolides of smaller size than the preceding, and with them no considerable amount of ordinary finely divided meteoric material such as comes to the earth.

It is also to be noted that since the earth's surface came to its present state there is good reason to believe that no such falls of large bodies as are supposed by the bolide hypothesis to have fallen upon the satellite have ever come to the planet. There are no traces of like craters, for even the greatest calderas, such as that which holds Lago Bolsena or Kilauea, are evidently volcanic and in no way related to meteoric action. Moreover, the fall of a bolide of even ten miles in diameter would, by the inevitable development of heat due to its arrest, have been sufficient to destroy the organic life of the earth, yet this life has evidently been continued without interruption since before the Cambrian time. The point to be last noted is that so far as I have been able to determine from an extended inspection of lunar craters, including several hundred of the more determinable, they all have the axes of their pits at right angles to the surface. Now if these pits had been formed by bolides encountering the moon in their movement, that movement necessarily being at planetary velocity, it does not seem possible that they could all have come upon the sphere in a path normal to its surface. Even with the resistance of the earth's atmosphere, which is far denser than that of the moon ever could have been, the small meteors which enter it mostly come at high angles to the surface of the planet, although its attractive power is more than eighty times as great as that of the satellite. It seems, indeed, incredible that if the lunar vulcanoids were due to bolides they should not have fallen in somewhat greater numbers on the earth because of its greater gravitative attraction. The number received would probably be nearly in proportion to the area of the two spheres, with a slight preponderance in the number falling on the earth because of its greater mass and consequently the greater effect of its gravity. It is, however, as before remarked, evident that no such falls as have formed the hundreds of pits over ten miles in diameter which exist on the moon's surface have occurred on the earth since the Cambrian age.

The foregoing considerations justify us in rejecting the hypothesis of falling bolides as a means of accounting for the so-called craters on the moon. There are, however, certain other features of lunar surface which may be explicable by the impact of large bodies falling from space. These we will now proceed to consider.

MARIA OR SEAS.

A large part of the surface of the moon is occupied by the so-called *maria* or seas. These are extensive irregular, indistinctly circular areas of relatively level nature and of a perceptibly darker hue than the other more rugged fields. This dark hue is shared by the floors of a number of the craters which lie near the seas, as for instance by that of Plato, and more rarely by craters which lie remote from their margins. Though vulcanoids exist on the maria of the moon they are of relatively small size, none, in my opinion, which have clearly been formed since the material of which the maria are composed came to its present level position, exceeding ten or fifteen miles in diameter. So far as I have been able to reckon, the proportion of these pits on the seas does not exceed one-fifth that we find on the other part of the lunar surface. The average discernible inclination of the surface of the maria is relatively so small they are more nearly true plains than any equally extensive land areas on the earth.

It is a noteworthy fact that the maria, though they occupy about one-third of the visible part of the moon, *i. e.*, including what is shown by the librations, rarely, if at all, lie on the margin, in positions enabling us to infer that they are parts of like areas on the unseen portion of the lunar surface. On the western limb of the sphere the so-called mare Australis is generally mapped as extending around the margin, as it in fact does at certain stages of the libration, but under the most favorable conditions the ordinary rough surface of the satellite appears to me to be visible beyond this small mare, so that the statement as to none of these seas crossing the limb apparently does not admit of exception. The ill-named mare Humboldtianum is evidently a vulcanoid. It therefore appears probable that if such maria exist on the unseen portion they are less extensive than on the part of the orb which we see.

The most interesting feature of the maria is found in their contact with the higher, rougher surface areas which bound them. Whenever I have been able to observe this contact in a sufficiently exact manner there appears to be good evidence that the material of which their surfaces are formed flowed in against or upon the rough ground as very liquid lava would do. In a general way this fact had been often noted. It fills in the lower ground forming numerous bays. In many instances, as, for example, in the case of Doppelmeyer, it distinctly appears to have melted down the side of the crater's wall next to it, and to have filled the cavity to its own level. Whoever will inspect these lines of contact of the maria with the higher parts of the moon throughout the several thousand miles of their extent will probably come to the conclusion that they were formed by the once fluid matter of the sea inundating firm land. Assuming, as I shall do, that these maria are made up of vast bodies of lava, which came upon the surface after the greater vulcanoids were made and, as we shall hereafter see, after some of the radiating light streaks were formed, how shall we account for the production of such bodies of igneous material? The quantity of this matter was evidently very great and in each of the seas it seems to have appeared all at once, there being no mark of successive flows such as compose the extensive lava fields of the earth. So far I have not been able clearly to trace any signs of contact or over-lapping of the lava of the several maria. The search is, however, difficult; no more has been ascertained than that the material must have been extremely fluid, far beyond what is seen in ordinary terrestrial flows. This is shown by the fact that although gravitative attraction is only one-sixth what it is on the earth, there is no steep face at the front of the fields, such as occurs from cooling of an ordinary stream of lava.

As for the origin of the lava of the maria there are few facts on which to base an hypothesis. What have been gathered may be briefly set forth. First, it is to be noted that none of the vulcanoids of the moon give forth freely flowing lava streams; it is, indeed, doubtful if any true lava flows have come from them. The features which suggest such streams are rare and rather inconclusive; they justify the statement that even the greatest, in general the earliest of the craters, and therefore those which should have had the largest amount of molten rock beneath them, show little or no signs of a tendency to extrude free flowing lava at the time when they were formed. Nor do any of the numerous fissures or faults of the lunar surface, some of which evidently penetrate deeply, distinctly give rise to lava flows. And we shall see when we come to consider the conditions of these volcano-like openings they appear always to have retained their lavas within or near their vents. Clearly these vulcanoid openings do not indicate any tendency of lava to pass up to the surface in large quantities.

It is an important point that there is no evidence in any of the maria that the lava comes from a central pipe or from an elongate fissure; their general form would seem to indicate that if the fluid came from within it should have emerged as from a terrestrial volcanic pipe, for if it came from fissures these should have been of elongate shape. But if it came either from fissured or from pipe-like openings there should be a grade to the flow extending from the center of the field to its margin; owing to the slight value of gravitation this grade should be steep. There seems to be no trace of such a slope; on the contrary, the curve of the terminator or margin of the illumination shows that they are essentially horizontal. It is difficult to believe that lava flowing from an opening for hundreds of miles could have this absence of slope. When it flows from a terrestrial crater the course is always short and very steep.

In view of all the facts, I am disposed to hold with Gilbert and other inquirers that the maria are the result of large masses falling upon the surface of that sphere. All the facts indicate that these vast sheets of lava did not come from the interior, and that the interior at the time when they were formed was not in a condition to yield any such masses of liquid rock. We are therefore fairly driven to this working hypothesis. In its favor we may adduce the following considerations :

The fall of a considerable body or bodies competent by the conversion of its momentum into heat to produce an extensive melting of the lunar surface, would be likely to develop melted lava under conditions quite different from that which is exuded from volcanoes. Assuming that the bolide came upon the surface at planetary velocity and that it was some miles in diameter, the heat due to the arrest of its movement would, we may fairly suppose, convert the whole of the body into a liquid if not into a gaseous state. A like result would occur in the part of the sphere which received the blow. Moreover, for some distance beyond the seat of impact the shearing strains would probably be sufficient to convert much of the material of the surface into the fluid state, with the result that a mass of lava at very high temperature, equal at least to the bulk of the invading body, and probably several times as great, would be sent at the speed determined by the gravitative value of the sphere radially from the point where the impact took place. It seems also, perhaps, a fair supposition that a great collision of this nature would temporarily form a heated atmosphere enveloping the moon, which would serve to delay the cooling of the molten rock until it had time to find its level. Yet the absence of any deposits of these temporarily volatilized materials is indicated by the fact that the light streaks are not obscured.

In favor of the hypothesis above suggested, it may also be said that the evidence of melting effected by the material which forms the plains of the maria is considerable at several points, notably in the case of the vulcanoids on the margins of the seas. It seems quite certain that the walls of these craters next the sea have been in some manner effaced by contact with the material which came against it. Again, as in Flamsteed in the Oceanus Procellarum, the crater wall has been almost melted down, but still rises slightly above the surface of the apparent inundation. At many points the material forming the mare comes against extended steep-faced cliffs, which have the same general character as the inner slopes of the great craters, where the form of the declivity pretty certainly has been determined by the melting action of the lava at the base. Furthermore, where there are depressions in the area on the borders of the maria, the material of which they are composed flows into them as a fluid would have done.

It is also to be noted that at many points where the maria come against gently inclined slopes the material of which they are composed appears to have at first flowed over these low but now unsubmerged areas and then retreated from them, leaving them in a measure smoothed as if by the in-filling of their cavities or perhaps by a partial melting of their projecting features. If such apparent inundation really occurred, it may have been brought about by the frontal wave of the lava which mounted, after the manner of those produced by earthquakes in the sea, for some distance above the permanent level of the inundation.

It may further be said in favor of this hypothesis as to the origin of the maria, that the material of which they are composed appears to have had throughout the whole extent of the several areas a singularly uniform fluidity. As before remarked, there are no signs of successive flows such as have always characterized the accumulation of the relatively much less extensive lava deposits on the surface of the earth. In this connection it should again be noted that none of the vulcanoids show any tendency to send forth extended flows, and the matter which appears to have been ejected to form the cones has evidently consolidated on very steep slopes. Thus, if the material of the maria was fluid when it came to rest, of which there seems no reason to doubt, it cannot have been poured forth from the interior in the manner of volcanic effusions.

The fact that the surfaces of the maria are of a distinctly darker color than the other and higher extended areas of the moon has some value as evidence that they have a peculiar origin, one not connected with the interior of the sphere. Certain of the crater floors have, it is true, about the same tint ; this is conspicuously the case with Plato. In this, as in certain other instances, the likeness may be due to the penetration by subterranean passages of the material of the neighboring mare into the cavities of the craters. There are, however, examples, as, for instance, the great vulcanoid Grimaldi, where the resemblance cannot be thus explained. Although these exceptions weaken the value of this evidence derived from the color of the maria, the uniformity of a tint which is evident in all of them and the seldomness of the exceptions tend to support the hypothesis that the rocks of which they are composed have not come from the interior of the sphere. This point will be further discussed below.

We turn now to consider the objections which may be made to the hypothesis that the maria were formed by molten rock produced by the impact of large bodies falling upon the surface of the moon. Of these objections, the first and, in many regards, the strongest is derived from the general consideration that like bodies competent to generate a great deal of heat have not fallen upon the earth's surface in the time which has elapsed since the beginning of the geological periods. There is indeed no geological reason for supposing that they have ever so fallen upon the planet.

Against the above-noted objection that the geological record of our sphere affords no trace of evidence of any such falling-in upon its surface of bodies of sufficient mass to produce widespread melting, and the proof that no cataclysms of this nature have occurred since the development of organic life, we may set the following considerations : first, that the moon's surface probably took its shape long before the beginning of our geological record ; and, second, that even in this late stage in the evolution of our solar system there remain bodies in that system in order of size such as would in falling upon the surface of the larger spheres produce the effect which we observe in the maria. Thus the group of asteroids which lie between Mars and Jupiter, though generally of far greater mass than would be required by impact to melt the larger of the mare fields, probably contains many bodies which, in case of collision with our satellite, would bring about the consequences we note. At least one such mass of matter, Eros, apparently not to be classed either with planets or satellites, has recently been discovered at no great distance from the earth. It is possible that in the relatively ancient state of the solar system, when the surface of the moon acquired its crust, these detached masses of matter were more abundant than they are at present. The tendency would be for those near the greater spheres to be drawn in upon them, with the result that they would become rarer near the planets and the larger satellites.

As for the origin of detached bodies of the bolide type, we have no basis for more than conjecture; we may, however, fairly suppose that the explosive action, which is of not infrequent occurrence in the fixed stars, may have happened in the case of our sun or even of the planets, with the result that masses of matter, perhaps originally gaseous or possibly in the molten state, were flung so far away that they acquired independent orbits.

Although the direct evidence going to prove that the maria are the result of the in-falling of large meteoric bodies is not complete, the hypothesis appears to me to have distinct value for the reason that the cause is sufficient to produce that evidently sudden development of large bodies of very fluid matter, which, for reasons before given, cannot fairly be supposed to have come from the interior of the lunar sphere. It is, in a word, the only working hypothesis that I have been able to find which in any way serves to explain these remarkable features of the lunar surface.

In considering the details of the maria it is to be noted that it is not necessary to account for all of them by supposing a single falling body brought about the melting. In several instances, especially in the case of the Mare Australis, and sundry other indistinct patches of the mare quality, the hypothesis can best be applied by assuming that a number of such bodies fell at about the same time and relatively near together. In this way we can account for the fact that in place of normal, rudely circular fields of melting, as in the case of the M. Crisium, we find an irregular, somewhat ragged field of this nature; in some instances with a periphery that suggests that there were several centers of dispersion of the fluid. Gilbert has maintained that the connected seas were formed by the in-falling of a mass upon the region occupied by the M. Imbrium. This view seems to me to be contradicted by the fact that in the passages between the connected maria there is no evidence of scouring action such as would have been brought about by the swift movement of great masses of lava.

It may also be said that the evidence of melting down of the pre-existent topography on the margin of the maria varies much. It appears most clearly in the case of the large, distinctly circular field of the Mare Crisium, and is least indicated in the irregular areas. Such are the conditions we should expect to find brought about by the fairly supposable variations in the size and number of the masses in any one fall. Thus, so far as my examination of the problem has gone, the supposition that the maria have been formed by sudden melting of colliding bodies and of the lunar surface about the point of collision appears to be warranted as a working hypothesis, though it has, perhaps, not been established as a theory.

To the suggestion that the surface of the maria is in general lower than that of the regions surrounding them, and that this fact is inconsistent with the addition to the quantity of matter in the area they occupy, such as would be brought about by the falling in of a bolide, the following answer may be made. In the first place, it is to be noted that the outer part of the moon is, except in the maria and in the crater floors, evidently characterized by a very open structure. It is prevailingly much occupied by volcanic openings, greatly rifted and probably composed of scoriaceous materials. If any such section as that about the Apennines were completely fused to the depth of some miles, it is likely that we would have a subsidence of the surface quite as great as that exhibited by the maria. In the second place, the bulk of the material brought by the bolide to the lunar surface would be small as compared with the volume of matter which would be melted by its impact. The proportion would probably be less than one to ten; so that the contribution from the impinging body would be so small that it would not be likely much to affect the general level of the melted area. The nature of the lunar surface in the maria and on the other more extensive regions will be further considered in the section on volcanic action.

As before noted, there is no series connecting the ordinary craters, however large they may be, with the maria. That this is the case is well indicated by the fact that selenographers have in only a few instances been in doubt into which group individual examples of these two species of lunar forms should be placed. The fields classed as seas, with the evidently related embayments thereof, termed sinuses or paludines, have always been regarded as readily distinguishable from the craters. This decision has not been made on the basis of well-described categories, but on the immediately evident differences between the two groups of forms. It is recognized that while nearly all the vulcanoids are essentially circular, or with only moderate distortions of that outline, the seas are as generally irregular in outline. So, too, it is patent that the vulcanoids, at least those of large size, have in all cases a fairly well-marked external slope or cone. None of the seas are thus characterized except where their periphery in part corresponds to some antecedent feature, such as the wall of a large pit which they have invaded, as in the case of Fracastorius, on the margin of the Mare Humorum, or where it encounters an elevation such as the Hæmus Mountains, on the southern border of the Mare Nectano. (See plate xxv.) This general acceptance of an essential difference between the vulcanoid floors and the seas, and the very slight doubt as to the classification of the level surfaces in one or the other, is excellent evidence as to their difference in nature.

The only areas of a level surface on the moon which may not be on mere inspection classed as maria or vulcanoid floors are a few large crater-form depressions situated near the eastern limb of the moon, of which the most important and doubtful is Schickard. Even a slight examination of this feature shows that it has a distinct continuous wall, and that the irregularities of its outline are due to the melting down of the borders of other craters as its area was extended in the manner which we shall hereafter see to have been common in the development of the larger crater-form pits. In other instances, as in Ptolemæus, the irregularity of the crater's shape may lead to doubt as to its classification, yet it is regarded by Elger as one of the most characteristic walled plains, its rampart being exceptionally good. A further analysis of the instances which at first sight appear to lead to some doubt as to the existence of a sharp line parting the maria from the vulcanoid floor leads to the same conclusion as the facts previously set forth, that these groups of level areas are, as structures, completely separated from one another, and therefore cannot have had like histories. In the one there has been a long-continued local volcanic-like action leading to the formation of an external rampart; in the other, a swift production of an igneous fluid, which has swept away until it found its level and shaped its margin by melting down the pre-existing reliefs.

Although in general the material which forms the floors of the several maria appears to be confluent, *i. e.*, to show no marks of overlapping at the lines of junction, there is reason to believe in the opinion of many observers that there is some diversity in the level of their floors. Thus the Mare Nectaris is supposed to be decidedly deeper than the others. This is not inconsistent with the view that they were all formed at nearly the same time. The greater depth of the last-named mare may be explained by the supposition that the absorption of the fluid matter into the ancient crust was relatively greater there than elsewhere.

While the surfaces of the maria are, as compared with the general surface of the moon, decidedly plain-like, they are, in fact, the seat of many irregularities. Of these the more important are a multitude of more or less continuous low-arched ridges, probably in no instance more than two thousand feet high, but uniformly of relatively great width, often several miles in transverse section. The nature of these ridges will be hereafter discussed. There are also on the maria numerous craters, none of them approaching in magnitude those on the old, more elevated portions of the crust. The ratio of craters on the maria is only about one-fifth as great as on equal areas of the original surface, and their average size is in about the same proportion. It is also to be noted that rifts or open cracks are apparently rarer on the maria than on the high lands and that the light bands and patches are of relatively seldom occurrence.

CLASSIFICATION OF VULCANOIDS.

In considering the so-called volcanoes of the moon (I shall term them vulcanoids), the first step should be a classification of their features. Selenologists have generally agreed to distribute them in seven categories termed as follows: walled plains, mountain rings, ring plains, craters, crater-cones, craterlets, crater pits. Besides these groups they recognize the existence of a less characteristic group to which they give the ill-defined name of depressions. Under the term *walled plains*, those who use this classification include the greater pits with the ring of high land about them. Elger selects Ptolemæus as the type of this group. He states that it is the distinguishing characteristic of this group that there is "no great difference in level between the outside and the inside of the walled plain"; he proceeds to cite notable exceptions to the rule, accepting Schmidt's term of transitional forms for them. These many exceptions range from Gassendi, where the interior plain lies at about two thousand feet above the floor of the Mare Humorum, which three-fourths surrounds it, to Clavius, where the interior is some three thousand feet below the general level of the area in which it lies; such variations are so numerous that they include practically all the differences in the altitude of the enclosed plain which we find in any of the groups. Nor are the other criteria of this category more characteristic. The irregularities in the walls, the clefts, breaches, and greater breaks, are, in proportion to the length of the encircling ridges, hardly more frequent than in the mountain rings or ringed plains. So, too, with the minor craters, cones, and ridges on the floors and rims; they are abundant, as inspection proves roughly, in proportion to the area and the age of the structure. A careful examination of this group of walled plains will satisfy the observer that they are essentially like the mountain rings except for certain accidents which have befallen the members of the last-named group.

Nearly all the so-called *mountain rings*, all, indeed, that I have been able to group in this category, lie in the maria. They appear, as has been considered by several selenologists, notably by Elger, to be the more or less ruined remnants of what were originally to be classed as walled plains. From their position in the maria and even more from their topographic features, they are fairly to be regarded as akin to the first-named group in origin and general history, save that at the time when the maria were in igneous fusion their rings were in part melted down and it may be in part breached by the tides of lava which surged against them. In some instances these mountain rings appear to have been suffused by the lava when it stood at its highest level, and afterwards bared as the surface of the fluid was lowered. The maria of the second and third quadrant particularly abound in these structures, in every stage of assault and demolition, from those which stood so high above the flood of lava that their exterior slopes show only slight signs of attack, to the intermediate stage of the broken ring immediately north of Flamsteed, and thence to sundry unnamed and scarcely recognizable fragments of rings in other fields of the maria. There seems, indeed, hardly any room for doubt that to establish this group we shall have to accept the principle that the state of obliteration of lunar formations affords fit basis for their classification. It appears to me that for my purpose this group must be rejected.

In the group of *ring plains* selenographers have grouped all the strongly walled vulcanoid pits of the lunar surface; they find the criteria for separating them from the walled plains in the more continuous nature of their ramparts and the steep declivity of their inner walls. They note also that there are often terrace-like structures on these walls such as would be produced by the successive stages of descent of the lava of the crater. Here again by the use of the method of series we may intimately connect the vulcanoids of this group with those of the two preceding groups. None of the students of this classification whose writings are known to me has failed to observe that there exist examples which may be classed as wall plains quite as well as ring plains. There is no doubt that these ring plains have in general better defined, more volcano-like cones than the wall plains, and that the contact phenomena of the lava of the floor with the inner slope of the rampart are more characteristic of volcanic action as we know it on the earth, yet these differences seem to me so to graduate together in the two groups as to afford no basis for distinct classification.

In the group of *craters* selenographers have placed so far the greater number of the vulcanoid pits. They have included in them nearly all the distinct pits from about fifteen to about three miles in diameter. So far as I have found, they suggest no definite criteria for the members of this group, save that they are widely distributed, occurring even on the walls of the large structures, and that on this and other accounts they appear to be newer than the wall plains or the ring plains. Inspection shows that there is no structural difference between the vulcanoids of this and the preceding groups, their relatively smaller size and apparent newness of formation affording no good basis for instituting a category in which to place them.

Following down in the order of size, the next accepted group is that of *crater-cones*. The objects included in this category are all of small size. Elger compares them to the parasitic cones of Ætna, which seems to me not a happy comparison, for their origin is in no wise related to the Ætna "parasites." As the pits are generally less than a mile in diameter it is difficult to determine the shape of their bottoms. My own observations agree with those of the selenographers, that these pits are usually in the form of inverted cones, terminating downward obtusely, *i. e.*, with no very distinct floors, and further that they are occasionally found with rounded, saucer-shaped bottoms, as if there had been lava in the cups, which had withdrawn with the cessation of activity into the deeper part of the crust. There is enough of this obscure flooring to connect by series the crater-cones with the craters, showing clearly that the difference between the two is one of dimensions alone and does not indicate any essential difference in the nature of the constructive actions. As regards the distribution of the crater-cones and craterlets, it is to be noted that they in certain instances appear to be associated with the light streaks; of this feature we shall take account hereafter.

The smallest of the observable pits on the surface of the moon are termed *craterlets*, or *crater pits*. These features are extremely numerous, the actual number on the visible part of the sphere, which might under favorable conditions be counted, amounting to many thousands. In the most characteristic specimens of this group there is no distinct wall or cone surrounding the pit, the opening often being abrupt, as if it were brought about by a mere subsidence of the area in which it lies. Yet here, too, there is a gradation, for in sundry instances there is trace of a ring wall as if some material had been extruded. In many instances these pits are not circular, but with irregular outlines, which further suggest that in certain cases there was no explosive discharge, but an in-falling of the covering of a pre-existing cavity. It is further to be noted that these craterlets often, perhaps oftenest, lie upon ridges, either the walls of the larger vulcanoids or the numerous elongate elevations which occur in great numbers on various parts of the surface and appear not to be connected with any large vents. In general it may be said that the craterlets are the smallest observable members of the series which has for its largest term the ring plains, and that they are among the newer features of the lunar topography.

Looking upon the variety of form of the vulcanoids of the moon in the light of our knowledge concerning the shape of terrestrial volcanoes, it may be said that the range in form is not very much greater in the case of the satellite than in that of the planet. Between the great caldera craters, such as those of the Sandwich Islands or the Bolsena group of Italy on the one hand, and the smaller cones on the flanks of Ætna on the other, we have a range in width of cup less considerable but approaching what is found on the moon ; or, comparing the nearly coneless craters of the Eifel, the products of a single eruption, with the peaks of the Teneriffe type or those of the Andes, we note a difference in the ratio of the enveloping cone to the interior which is also comparable to that exhibited by the lunar vulcanoids. It is evident that the series of lunar craters has much ampler range in diameter than those of the earth, but the correspondences are sufficiently evident to justify us in including all such features of our satellite in one group, assuming that the conditions of their formation were probably as near alike as in the several varieties of terrestrial volcanoes. An inspection of the lunar vulcanoids shows us that the most important features which separate them from those of the earth are to be found in the amount and nature of their extrusions ; the order, or lack of it, in their positions on the surface ; and the influences which have served to deform or to destroy their features. These peculiarities will be considered below.

The presence of a level surface of frozen lava in all of the lunar vulcanoids save perhaps the very smallest is, as compared with the volcanoes of the earth, their most conspicuous feature. This clearly indicates the relatively languid nature of the eruptions from those craters. There are, it is true, a number of terrestrial volcanoes where such a floor exists, but in all cases the facts justify us in supposing that the last eruptive action was of the milder type, as in the case of Kilauea in the Sandwich Islands. Eruptions of even slight intensity measured by terrestrial standards result in blowing out all of the fluid rock. Thus we are justified in regarding the level interiors of these vulcanoids as evidence that the normal lunar crater did not discharge explosively in true volcanic fashion. If such violent discharges took place at any stage of the history of our satellite they appear to be unrecorded in its existing features.

Not only is the presence of lava shaped on a floor in all the hundreds if not thousands of distinctly observable lunar pits proof of the non-explosive nature of their eruptions, but we have other evidence to the same effect in the lack of all signs of ejected masses and of dust-showers, such as are the most striking phenomena of terrestrial outbreaks. If we select any of the vulcanoids situated in a region of much accidented topography, which evidently existed before the vent was formed, and examine the surface about the opening, we readily note that it is not masked as it would be in case it had been subjected to a succession of ash showers such as come from a normal terrestrial volcano. In many instances I have observed that there was no trace of such ash-covering up to the very foot of the ring wall. Like evidence of a more affirmative nature is to be had in the very numerous instances in which one vulcanoid cuts another. So far as I have been able to note the details of these instances, the earlier existing crater, except where its walls have been deformed by the encroachment of its neighbor, never suffers from any distinct obliteration. Its ring wall—craterlets, vents, terraces, and other slighter features, which should be hidden or distinctly changed in aspect by an accumulation of even a few score feet of ash—remains, so far as can be discerned, unaltered. When we remember that there has evidently been no erosive action on the moon such as has normally washed away thousands of feet in thickness of ash about Ætna and other large terrestrial volcanoes, we see how clear is this evidence that the lunar vulcanoids have not been the seat of ordinary volcanic explosions.

The lack of considerable lava flows on the moon appears to be almost as well established as the absence of ash ; in but a few instances have structures which can possibly be classed as flows of really fluid matter proceeding from craters been reasonably suspected, and these on inspection appear to be more than doubtful. As will be noted below, the material in the craters appears not to have had a high order of fluidity, so that it quickly consolidated on very steep slopes—according to my observations generally exceeding 20° of declivity—as soon as it passed out of the cup. None of the rills or other fractures appear to have afforded passage to the interior fluid material ; they seem, indeed, to have been formed long after the larger vulcanoids had ceased to be active.

DISTRIBUTION OF VULCANOIDS.

In considering the distribution of the lunar vulcanoids it is first to be noted that, unlike those of the earth, they are scattered over the whole of its visible surface. The fact that here and there all around the limb we may trace the hither borders of great ringed plains fairly leads to the supposition that like structures exist on the unseen portion of the sphere. Except that on the maria there are no large vulcanoids formed since those great plains were produced,—probably none as much as ten miles in diameter that postdate their fluid period,—there is little to be said concerning the distribution of these features on their surfaces. There are, it is true, considerable areas of the lunar surface outside of the maria where the only vulcanoids are the craterlets. With slight exceptions these are the regions of so-called mountains, or in fields where there exist very many low dome-like elevations, often circular in outline but occasionally somewhat elongate. Of those regions where vulcanoids of considerable size are rare, the most noteworthy are the field of the Hæmus Mountains, the region on the west side of the Mare Fœcunditatis, and that to the northwest of the Caucasus Mountains, though there are many others of about the same extent. (See plate XVIII.) Several of these regions are of more than fifteen thousand square miles in area. It should be understood, however, that none of these fields entirely lacks vulcanoids; it is indeed doubtful if there is any part of the moon's surface, except it may be some portions of the maria, where craters of large or small size may not be found in every circle of twenty miles in diameter.

In many accounts of the distribution of the lunar vulcanoids it is stated that the greater of them exhibit a distinct train-like arrangement. As before noted, I have been unable to find any satisfactory evidence of such order being at all common. Here and there, as in the group of Ptolemæus, Alphonsus, and Arzachel, there is a trace of linear order, but a study of the facts shows that so far as the larger structures are concerned there is no reason to believe that there is any prevailing definite order in their placement. There is, however, good reason to believe that the smaller vulcanoids, commonly termed craterlets, are not infrequently arranged in linear order. This is not true of all of them, but is clearly so in the case of those which are in some way related to the rills or other crevices, and to the light rays of this point I shall have more to say below.

As regards the order of distribution in time of the lunar vulcanoids, it may be said that all the facts point to the conclusion, if they do not establish it, that the largest of them commonly were formed first. This is shown by the fact that in only a few instances does a large ring plain cut a decidedly smaller structure of the same nature, while the instances in which the smaller have intersected the larger are very numerous. So far as I have been able to apply this method of determining the relative age of the rings, it establishes the fact that the greater number, if not all, of the vulcanoids of say over fifty miles in diameter were completely formed before the most, if not all, of those say twenty miles in diameter were built, and further that very many of the craterlets were opened after the greater structures were completed. Still further it appears likely, though not certain, that before the greater vulcanoids were formed the so-called mountain districts and the general surface of the moon had acquired the topography we now find them to have, at least as regards the larger features of the surface. In very many of the great vulcanoids we find evidence that the neighboring country has had its surface somewhat distorted by the intruding structure. In a word, there appears to have been an ancient surface antedating the distinct ring plains, though it is possible that this surface was itself largely made up of such rings which have been obliterated by the agents of decay, which have in many instances partly demolished structures which are still recognizable, though often but faintly. The number of these faint rings too indistinct to be named, and rarely affording more than the merest traces of their original form, is so great as to warrant the conjecture that those now existing are but the last of a long series which has been formed and destroyed. Close attention to these features in the moments of good seeing, which occasionally reward the observer, will reveal a series connecting such still distinct though extensively demolished rings with other more numerous fragments of circles which would not be interpretable save for the connecting links.

It may here be said that the phenomena of dilapidation exhibited by the relicts of ring walls in the fields of the maria differ essentially from what we find on the outlying surface of the moon. In the last-named areas, the ruining of the ancient ramparts has evidently been in large measure brought about by the encroachment and possibly by some shearing pressure of later-formed vulcanoids, which actions have broken down and shoved about the fragments of the once complete circumvallations. In addition to these processes of burial and displacement, there have apparently been at work some influences which have slowly broken down the rings, so that they have lost the original steepness of their profiles. In and on the borders of the maria we find evidence that the destruction was brought about by the immediate and swift assault of the originally fluid material that now forms these plains of frozen lava. The rings are not deformed but more or less broken down, in part breached, by the stroke of a tide of fluid rock, as in the case of Doppelmeyer and Hippalus on the shores of the Mare Humorum, or simply overflowed and melted down, as is the case with the great unnamed ring north of Flamsteed, the more effaced ring between that structure and Damoiseau, or the many other like instances in other maria.

As we pass from the largest rings downward in the series towards the smallest craters which have distinct floors, we note a progressive increase in the freshness and finish of these structures. The departures from the original form become less frequent, the walls are less breached, and the slopes of the ramparts steeper and more even. The interference of rings of like size becomes rare, so that with those less than five miles in diameter it does not appear to occur. All these facts point to the conclusion which finds expression in the writings of many selenographers, that in general the larger the rings the greater their age.

PHYSICAL HISTORY OF THE VULCANOIDS.

Comparing the lunar vulcanoids with the terrestrial volcanoes and adding to the considerations no more than a reasonable amount of conjecture, it seems to me that we may interpret the phenomena as set forth below. In this explanation care has been taken to introduce into the interpretation nothing in the way of action that does not appear to be warranted by the processes of our own sphere.

It is, in the first place, evident that while the lunar vents indicate some process of eruption it cannot be regarded as in its nature identical with that of ordinary terrestrial volcanoes. These last-named craters are, while they remain active, with rare and questionable exceptions, on sea-floors or near their shores. What we observe in their action and their distribution leads us to believe that they are—mainly if not altogether—the points of discharge of water-vapor or of its dissociated gases, and that this water has been buried by aqueous sedimentation. The result is that when heated to a high temperature the fluid commonly explodes with a great tension, scattering large amounts of morcellated rock to great distances from the place of escape. On the other hand, in the lunar vulcanoids, the evidence goes to show that there were no explosions competent to drive fragments in extended trajectories. It is evident, indeed, that the movement of the lava in the pits was almost exclusively up and down in the cavities, often with successive haltings on a particular level, followed by a sinking to a considerable depth. In these stationary periods, the terraces of the frozen fluid on the inner slopes of the ramparts apparently were formed. That the position of the lava was not in all instances determined by a common interior deep level of the fluid seems to be shown by the fact that in some of the rings its surface is several thousand feet below the surrounding area, while in the case of Wargentin, just south of Schickard, the floor apparently lies high above the surface of the surrounding country.

That there was some kind of boiling or up-welling action in these crater lavas is well shown by the fact that in a number of instances, more numerous than the records show, the surface of the floor is flexed upward, so that the center is some hundred feet above the rim of the sheet, as if the final much weakened impulse was sufficient to arch the frozen crust but not great enough to rend it from its adhesions to the shore. Such tumefying action is also shown by the numerous instances in which a mountainous mass of lava has been forced up in the central part of the crater floor. These medial heaps of lava are so common in the vulcanoids of middle size as to be the rule rather than the exception in these structures. In many instances they are replaced by central craters, or now and then, as in the case of Theophilus, there is a mass spewed up, as are some terrestrial trachytic cones, with only a faint trace of crater pipes leading downward into the interior. (See plate XVII.)

Finding as we do evidence of some swelling and sinking process competent to lift and lower the lava in the craters of the vulcanoids, and seeing at the same time that this action did not take place with anything like the energy of terrestrial eruptions, the question arises as to the nature of this eruptive force which has operated on the crust of the moon. The only hypothesis which has suggested itself is some kind of boiling, such as will take place in any fluid mass which is heated below and cooled on the surface, as in molten iron, where substances in the vaporous state, though they exist, are not present in sufficient quantities greatly to affect the movement, or there is a circulation mainly impelled by the escape of imprisoned vapors. Mere convection of heat in an igneous fluid does not seem to be sufficient to account for the rise and fall of the lava in the craters, especially as in the case of Wargentin, for there the lava floor lies at a height of some thousands of feet above the general level of the surface. We will therefore consider the possibility of there being materials vaporized by heat in the lava, not enough to produce the type of terrestrial explosions, but sufficient to lift the lava to the tops of the existing rings and to produce a circulation sufficient to keep the material for a long time in a molten state. On this point we have some direct evidence from the fact that many types of lavas that form dykes, such as granites, are violently forced into rocks of the earth's crust without there being any evidence of vaporous or gaseous materials impelling them ; it is more likely, however, that what we see in the way of eruptions on the moon are the results of extrusions brought about by the pressure of gases originally contained in the fluid mass of the sphere.

It is commonly assumed that for a long time after any celestial sphere has entered on its fluid state, in passing from its nebulous or fragmentary previous condition, the process of separation of its materials volatilizable at the temperature established by the concentration must necessarily go on with the result that some such vulcanoid phenomena as appear on the lunar surface will be likely to occur. It is a fair working hypothesis that every crater-like opening on the moon was formed by the relatively mild outbreak of vapor such as keeps open the terrestrial craters of the Kilauea type ; in such vents there may be vapor enough to induce some movement of the lava, but not enough to cause very great ejections of the fluid.

It may be assumed that the lava of the moon far more than that of the earth would tend to retain its gases and to form the viscid, slow-moving material known as pumice, which even when near a melting temperature is of a wax-like stiffness. The reason why the blebs of vapor could not separate from the lunar lava as readily as from the fluid rock of our planet is to be found in the relatively slight value of gravitation, which on the surface of the moon is only a little more than one-sixth what it is on the earth. The tendency of bubbles to separate from a fluid depends in large measure on the difference between the weight of the contained vapor and that of the mass in which they lie ; so that it may well be that the lavas of the satellite were on account of their contained vesicules of vapor less fluid and more like pumice than those we have a chance to observe in volcanic action.

When the lavas were lifted to the edge of the encircling rampart it is evident that they flowed out. That they were in the periods of activity so lifted and discharged is plain from the height of the terraces in many lunar craters, and from the elevation at which the lava floor has remained in the case of Wargentin. The normal well-preserved vulcanoid of sufficient size to permit a study of its features shows, in most instances, buttress-like ridges extending not more than a few miles outwardly from its rim ; these are fairly to be taken as flows which have passed over that rim or through breaches in it. It is to be noted that all of these buttresses have very steep slopes, both in the radial direction from the crater and laterally from the center of the ridge. To those accustomed to the gradual slope of lava streams, such as break forth from the base of volcanic cones where the angle of declivity is often not more than two or three degrees, the twenty to thirty degrees of inclination of these supposed lunar flows may seem to negative the hypothesis that they can be lava streams. Lyall and others have, however, shown that lavas may, flowing over the edges of terrestrial craters, consolidate in slopes of eighteen degrees of declivity. Now the angle at which the stream comes to rest will, other things being equal, be determined by the value of gravity; reckoning this as before at one-sixth that of the earth's surface, we see that a very much increased slope may well be allowed in the case of the lunar discharges.

The conception thus formed of the process by which a lunar vulcanoid of the larger size was produced, a conception founded on an extended study of their phenomena, is as follows: the first stage of the action probably consisted in the production of a slight dome-shaped elevation such as abound on the lunar surface, being, indeed, the commonest of the smaller features on many parts of the areas outside of the maria. These dome-like elevations appear to be due to some accumulation of vapors beneath the superficial layer, formed perhaps when the whole crust was still partly softened by heat. At a certain stage of the process this arch fell in, or was broken to pieces and thrown outwardly, leaving a pit with lava in it. When in its oscillations of height this lava overflowed the edge of the pit, the material so passing from the heated interior quickly consolidated and began the formation of a ring-shaped rampart. With the continuance of this action the lava would tend to melt down the interior faces of the rampart, gradually extending the diameter of the opening, destroying and remaking the wall as the process of enlargement went on. Finally, as the supply of melted rock was by unknown causes reduced, the lava fell to its lowest depth and gradually froze; the last stage in the activity being usually marked by a small central crater, a low dome, or by a spewed-out cone, such as so commonly occupies the central part of the floors of the greater rings. It is to be noted that the present position of the lava in the vulcanoids is not to be taken as its average height, for practically all of the craters which preserve what seems to be a fair semblance of their original form show the remains of terraces that indicate higher levels of their floors.

The objection may be made that the summits of the ramparts abound in peaks which rise far above the general level of the rings. It is evident that these salient points present serious difficulties; in some instances they may be accounted for on the supposition that the parts of the ridge now much lower have been broken down by lava which has poured over its crest. In other cases we may find the explanation in the fact that there is an obvious tendency to form small craters on the crust of the ring wall, there being many such that are plainly visible. Now, as we see elsewhere, particularly in the center of the vulcanoids of middle size, sharp, irregularly shaped masses of extruded lava, sometimes, as in Theophilus, many thousand feet high, often take the place of small craters. (See plate XVII.) Thus these isolated peaks may be masses of lava which have been spewed up to a great height. The origin of the small vulcanoids on the ramparts of the greater is a difficult matter to explain; it may perhaps be accounted for by reference to terrestrial volcanoes, where we find some evidence of a like tendency to form secondary craters around the margins of a plug of frozen lava which fills the cup. If we suppose a ring widening by the process of melting and rebuilding its walls, we may conceive that the fluid is likely to extend at points beneath the ramparts, so that when, after a period of repose, in which the lava was frozen and had shrunk, activity was resumed, the easiest way upward for the vapors would be by passages leading vertically through the wall.

The curious fact may here be noted, that in no observed instance is there distinct evidence of any lava flow which has broken under and through the rampart or cone surrounding a vulcanoid. When we consider that practically all the lava streams from terrestrial volcanoes break out through the base of their cinder cones, this condition of affairs on the moon demands an explanation. This may, like many other of the lunar events, be explained by the fact that the weight of the fluid, which is the impelling agent of its flowing, is only one-sixth that of terrestrial lavas, while the cohesion of the rocks may be, and most likely is, quite as great as on the earth ; certainly these cones, which apparently are far more firmly built than the ash heaps of volcanoes, must have resisted the relatively slight hydrostatic pressure of the lavas they enclose far better than the like structures of the earth.

We may here turn aside for a moment to consider the hypothesis that the evident and often probably repeated up-and-down movement of the lava in the vulcanoids was due to tidal action effected by the earth. While it cannot be doubted that the effect of the earth's attraction, at present six times as great on the moon as is that exercised by that body on our sphere, and may of old have been yet greater, would be competent to lift any internal united mass of fluid to a considerable height, there are reasons why it cannot well have served to pump the lava up to the elevations it attained in the lunar craters. To be operative, we have to suppose that the terrestrial attraction took effect in a central mass of igneous fluid, the surrounding crust being essentially rigid, not flexing to any great extent with the pull, which seems to be an unwarranted assumption. Under these conditions the lava would mount and descend in each lunar day, which, before the moon ceased to have a diurnal rotation, may have been of almost any length less than what exists at present which we have a fancy to reckon. It is, however, to be observed that the lavas of the vulcanoids, from time to time, froze at exceedingly varied levels, there being a range of several thousand feet in altitude in craters which are near to one another. These stations of repose, long enough to permit the freezing, are not to be explained on the hypothesis of incessant tidal pumping ; nor have I been able to account for the facts by any warrantable subsidiary hypothesis. Moreover, the smaller vulcanoids, the craterlets, which are evidently in the same series as the greater, having little or no lava in their bases, cannot be thus explained. Furthermore, the central cones of many of the larger vulcanoids, the formation of which was evidently in some way connected with the actions which built the whole structures, apparently cannot be brought under this explanation.

The most reasonable view as to the interior condition of the moon when its vulcanoids were in activity is that it was in a state of essential fluidity with a relatively thin crust. This fluidity may not have been that of terrestrial lavas; it may have been, and apparently was, more viscous or pumiceous. That such was the case is suggested by the behavior of the extruded lavas; it is further supported by the form of those other extrusions which occur in the so-called mountains, as will be further noted in the study of those structures. Thus the crust, despite its being of greater weight than the interior lavas, may have attained a considerable thickness; it may have had a depth of some miles. Yet it is hard to believe that it would have formed a sufficiently rigid enclosure of the interior fluid to have caused the sphere to remain undeformed by the earth's attraction to the extent necessary to bring about a great up-and-down play of the lava in the passages leading to the surface. It is furthermore to be noted that no trace of tidal action has been observed in terrestrial volcanoes — though this fact may be accounted for by the difference in the nature of their origin.

I have already, in preparation for the study of the maria, considered the arguments against the supposition that the vulcanoids are due to the in-falling of meteoric bodies, the main point being that they fail to exhibit any trace of the great melting due to the collision of bolides of sufficient size to make such pits. The maria being, according to my view, due to such in-fallings, showing all the evidences of a vast and sudden development of very fluid material of high temperatures, it follows on this hypothesis that the vulcanoids cannot be due to like action. The objection to this explanation in the case of all the crateriform openings seems to me to be so insuperable that it may not be further discussed.

It is important to consider the group of vulcanoids which have been formed on the surface of the maria since the lavas of the maria were produced. We note, at the outset, that these openings are all of relatively small size. Leaving out many doubtful cases, where it is not easy to determine whether the structure was in age antecedent to the maria in which it lies or no, these vulcanoids, so far as I have observed, never exceed ten miles in diameter, and even those of such width lie in positions where the covering of lava proper to the mare may be thin. It is therefore possible that they are due to actions occurring beneath this marial sheet which have manifested themselves on the new surface. The only vulcanoids which may be with some confidence regarded as having their origin in the lavas of the maria are the numerous small craters and craterlets, those in general of less than a mile in diameter, which are abundantly found scattered over their fields, though they are there less numerous than on certain other parts of the lunar surface.

It may here be noted once again that in certain instances the likeness of color and the relation of height of the lavas of the maria and those of large nearby craters leans to the suggestion that the igneous fluid from the neighboring mare passed under the ring wall, or through clefts since effaced, into the area it encloses. This view is most distinctly suggested in the case of Plato and Grimaldi, but there are other instances to which it would be applicable. Such a passage of lavas by underground ways is made doubtful by the fact before adverted to, that in no instance has the molten rock contained within a ring been observed to discharge itself through the rampart, as is often the case in terrestrial volcanoes. It is perhaps more likely that any communication with the maria was by fissures in the walls which have since been closed, or, if remaining, are so narrow as to escape observation.. It may be said, however, that the great heat of the marial lavas and their evident high fluidity would have enabled them to burrow through passages not permeable to the viscous lavas of the vulcanoids.

The evident fact that the order of succession in time of the vulcanoids is, in a general way at least, in the order of succession of their size, the larger being the more ancient, enables us approximately to determine at what stage in the lunar surface the maria were formed. All of these several areas which have originated independently one of another appear to have about the same sizes of minor vulcanoids on their surfaces. The small craters apparently originated after the greater rings had been formed, but certainly before the discharge of materials from the interior had ceased. It is possible, however, that all the vulcanoids in the maria, except those which were situated on such elevated ground that they were not suffused by their lavas, owe their origin to boiling action within the liquefied zone of the seas themselves. In this case it is possible that the time when these fields were formed was after vulcanoids ceased to be produced on other areas of the lunar surface. The general sharpness of these structures on the maria is in favor of their relatively recent origin, though it affords no data for a precise determination of their age.

I have, in considering the origin of the maria, referred to what appears to me to be evidence that the fluid of which they were originally composed had extended upward along portions of and perhaps all of their shores, so as to produce a smudged effect on parts of the relatively low-lying ground. So far as I have observed, this apparent effect is most evident on the southern shores of the Mare Nubium and the Mare Humorum. (See plate XXI.) My observations suggest that these apparently inundated fields lack craterlets, such as occur on the areas of the distinct maria. If this observation should be confirmed, it would make it likely that the seas were formed after the activity of the moon, as a whole, had ceased, and that the craterlets of the maria were due, as just above suggested, to boiling within their masses, and not to the internal fluid of the sphere. A careful reckoning of the number of very minute craterlets on the maria, as compared with those on other parts of the moon, will probably show that they are on the average more numerous on them than on some other fields of higher ground, and also that they are of prevailingly smaller size. As a group they appear to me to grade less distinctly into the flat-bottomed craters than do those of the highlands. My observation on these points are, however, not sufficient to more than suggest these possibilities. Anything like a determination of them demands better seeing than is to be had at the Harvard College Observatory and better sight than is now mine. Should these variations really exist, they would tend to show that the maria had developed their vulcanoids from their own materials. In further inquiries concerning these pits on the maria, it will be well to have them compared with like structures in the lava floors of the larger ring plains. My inspection shows them to be very similar in aspect, as they may be in origin, probably being both alike due to actions taking place within a moderate distance from the surface.

MOUNTAINOUS RELIEFS OF THE MOON.

Next in topographic importance to the vulcanoids come the reliefs, which have received the general name of mountains. In this group we find at least three distinct categories, which probably are due to as many separate causes. First and most important of these species of salient forms come those which have generally been named after terrestrial ranges or orogenic systems, as, for instance, the Alps, Apennines, Caucasus, etc. Although these groups of elevations have a considerable local diversity in character, varying in elevation from two or three thousand to twenty-six thousand feet or more, and in shape of their individual peaks from seldom nearly conical forms to much extended ridges, they in general have the character of elongate masses rudely elliptical in horizontal section, the several units of each field showing a tendency to a rude parallelism of their axes. These units are rarely distinct from one another, but connected at their bases, so that the field they occupy is by their confluence considerably raised above the general surface of the country in which they lie.

The number of these fields of mountains which have been named by selenographers is about twenty-five. There are, however, probably at least twice as many areas which exhibit this type of structure in a tolerably clear manner. One of the most important of these is the area between Schröter on the south and Marco Polo on the north, the area in part forming an isthmus-like barrier between the Mare Nubium and the Sinus Æstuum. The facts go to show that while the tendency to form this type of topography is more evident in the northern than in the southern hemisphere, it has existed in some measure on all parts of the moon except those now occupied by the maria; in these fields, though there appear to be ill-preserved remains of such structures, they are very imperfect. It may also be said that structures of this nature seem to be more frequently developed near the limb than elsewhere, but this may be due to errors in classification, consequent on the difficulty of determining whether elevations in that part of the surface are the borders of vulcanoids or mountain ridges.

In considering the relation of the mountains of the moon to the vulcanoids, it is important first of all to note the fact that where they are extensively developed there is a prevailing absence of larger crater-form structures, and that in certain instances we may at least suspect that they have broken up such structures. At a number of points involved in these tangles of ridges there are features which look very much like fragments of the rampart of ringed plains which had been involved in the apparently tumultuous movements attending the building of the mountainous reliefs. Instances of this nature occur in nearly all the larger mountainous areas; good examples exist in the Hæmus Mountains and in the unnamed district between the Lacus Somniorum and the Mare Crisium. As it is the habit of the ridges to be rather straight, the occurrence of curved fragments, varying from those of a few degrees of arc to half circular, appears to warrant the hypothesis that antecedently existing vulcanoids have been broken up in this peculiar constructive work.

In some instances vulcanoids which were evidently once fairly perfect, as such structures necessarily are at the time of their formation, have been apparently invaded by the mountain ridges. This is the case in Marco Polo, just above mentioned. Here an originally normal ring plain has been broken into on its northern versant, and thereby so deformed that its original nature is not readily perceived on casual observation. The great walled plain of Hipparchus appears to have been in large measure destroyed by the development of mountain ridges, which traverse its walls and in part the enclosed plain. Many other instances could be cited to show that these mountain-building actions, whatever their nature may be, have been very effective in deforming if not in destroying the vulcanoids of large area. Even the generally well-preserved Plato appears to me to exhibit in its wall evident traces of dislocation arising from the disturbance of the moderately accidented region about it.

There is no evidence sufficient to determine the stage when the building of lunar mountains ceased. There is, however, reason to suspect that they were not formed after the maria came into existence. There are, it is true, a number of groups of such structures which lie within the boundaries of the seas, but there is some reason to believe that these are the survivals from an antecedent time, being parts of systems which were not entirely buried by these widespread lava fields, though they show to my eye distinct evidence of having been effected by the inundations of liquid rock. If this judgment as to the history of the intramarian ranges be accepted, then we may safely conclude that the mountain-building period was passed before the seas were formed. There is some reason to suppose that this stage of the lunar development did not extend down to the time when the smaller vulcanoids, at least those which lie outside of the ring plains, were produced. In no instance have I observed any of the mountainous folds breaking in upon craters less than ten miles in diameter, though my observations are not sufficient to completely exclude such occurrences. In many instances, however, very well-shaped craters of several miles in diameter occur in mountain-built areas. They often are so well preserved that we have to exclude the supposition that they were formed before the ridges were developed.

The second group of prominences which may be termed mountains has for its type the isolated masses which often occur in the central parts of lava floors of the greater vulcanoids, and more rarely in excentric positions on those floors. These reliefs were evidently produced by some action connected with the formation of small craters which they appear to replace. Such craters on the floors of the vulcanoids are, as is well known, extremely common; in many instances there are more than a dozen within the ring, and in the Stadius Schmidt says he counted fifty, and forty-one have been delineated. Commonly there is either a considerable pit or a mountain in the center of the ring, the probability of this central feature occurring being greater with the decrease of the size of the vulcanoid, until the diameter of the plain becomes less than about ten miles, when it tends to disappear. The facts indicate that the central pit and mountain of the vulcanoid floor are interchangeable features. In some cases the peak has a more or less distinct craterlet upon its summit, or, as is shown in the central compound structure of Theophilus, there may be traces of a crater masked in the extruded heap.

The third group of reliefs on the lunar surface is typified by the long, low, apparently continuous ridges which are found on all the maria, but which are particularly well developed on the Mare Imbrium, the Mare Serenitatis, and the Mare Nectaris. (See plates XVIII and XXIV.) The characteristic features of these ridges are their prevailingly low-arched forms, their slight height, and their remarkable continuity; they very often attain a length of one hundred miles, and in some cases of twice or thrice that extent, while the greatest elevation assigned to them is less than two thousand feet. As their flanks grade rather indistinctly into the general surface of the maria, their precise width cannot be stated; it is evidently variable, with a probable maximum of five to ten miles. So far as I have been able to ascertain, well developed continuous ridges are limited altogether to the maria and practically so to the larger fields of this nature; in the small maria they are much less distinct, though there are instances of slight undulations which may belong in the same category of structures. In fact all the extended plains, even those of the greater vulcanoids, exhibit more or less wrinkled surfaces, when seen with powerful telescopes under very oblique illumination, such as serves to bring out irregularities only a few score feet in height.

The distribution of the continuous ridges indicates that they belong to two distinct groups which may be due to diverse causes, or at least to different methods of action of some general cause. The most evident of them are often nearly rectilinear, or with broad curves, which have no evident relations to the outlines of the shore of the mare in which they lie. Of these, the great examples extending from near Lambert in the Mare Imbrium, or those of the Mare Serenitatis lying between Posidonius and the promontory of Acherusia, may be taken as types. Another group, well indicated on the borders of many of the maria and some of their embayments, has the folds following the shores and seems to be limited to a somewhat distinct field lying near those shore lines. Elger suggests that in the case of Mare Nectaris these shore-following ridges are due to the settlement of the lava in the central part of the basin. It is undoubtedly the fact that the lava has been lowered in the Mare Crisium since the surface has frozen, as it probably has in all the maria; traces of like action seem to me to be more than conjecturable in the floors of the larger vulcanoids as well; but it is not to me clear that these shore-following wrinkles are, as Elger suggests, caving-in steps, such as those formed on the edges of a frozen pool or stream as the water in the basin subsides. If they are, as some of my sketches indicate, arranged in the manner of a carpet on a stairway, as monoclinal folds of terrestrial rocks, we have reason to suppose that they are due to faults which skirt the shores and which occurred in the basement rocks while the lava sheet was still in a plastic state. This supposition has its difficulties, for there is no evident reason why such faultings should occur; faults with vertical displacement are very rare on the surface of the moon, and in no case are they found in any such order as we need to have them to account for the shore wrinkles like those curving around the borders of the maria.

Less distinct than the typical continuous ridges, but probably to be connected with them, as lesser phenomena of the same order, we have, as before noted, on all the maria and on some of the greater vulcanoids' floors, faint wrinkles of great linear extent. The relation of these to the larger ridges appears to be confirmed by a series in which it is impossible to determine any break. I am therefore disposed to place all the elongate wrinkles in one group, regarding the typical examples hundreds of miles in length as structurally related to the slight, relatively short foldings which are barely revealed by the telescope. On close examination of the more characteristic elongate ridges it appears likely that they are not, as they appear at first sight to be, even arches, but in some instances at least are compounded of smaller wrinkles arranged in a more or less parallel order. As these minute features are discernible only by their shadows, it is as yet undetermined whether they are subordinate ridges forming a kind of chain or fractured blocks. I am inclined to think it probable that they are of the last-named nature, for the reason that analogy with terrestrial lavas would indicate that solidified superficial lava would fracture and not fold into arches. Some of these ridges appear to have craterlets on their summits.

It is also to be noted that, while the systems of low elevation which we are considering have great continuity, there is an evident tendency to break the continuity, so that the chain is composed of separate links, each parted from the other, as in terrestrial mountain chains. Here and there these units are arranged in an echelon order, as is the case in many terrestrial mountain chains such as the Alleghanies. This arrangement makes the likeness of these lunar elevations to terrestrial mountains more evident than any other of its reliefs.

A third group of lunar elevations, possibly akin to the long ridges above described, is found in the domes which abound in many parts of the surface; they are, according to my observations, commonest on those parts where vulcanoids are rare. I have suggested that certain, or perhaps all of them, may be incipient craters. These domes are found on the maria, though here they are of prevailingly smaller size, as well as on the older, more elevated surfaces; in number they rival the crateriform structures. Following the plan of grouping the lunar features, when possible, into series, I have endeavored so to connect the domes with the elongate arches before described. There are many examples of domes which are somewhat elongate, say with the major axis near twice the extent of the minor, but I have not been able to unite the two groups by any complete series of transitional steps and therefore am led to consider them as possibly distinct.

ORIGIN OF LUNAR MOUNTAINOUS RELIEFS.

As regards the origin of the first-described groups of lunar reliefs, those which form the massive elevated mountains, it may be said that they cannot be placed in the category of terrestrial structures due to folding and faulting combined with aqueous erosion. If there be any one certain fact concerning lunar topography it is that it nowhere exhibits the results of water erosion. If orogenic action such as operates on the earth has acted on the moon, as it may have done in the case of the elongate ridges of the maria, it could give us no more than arches and the fractures incident on their formation. It could not possibly have developed the steep, lofty, and extremely serrate structures such as are found in the greater fields of the so-called mountains. So far as geology enables us to interpret them, these elevations must be due to the ejection of exceedingly viscous lavas, forming heaps such as we have in certain masses of trachytic rocks on the earth. That such ejections do occur on the moon is well shown by the very numerous and often high peaks which have evidently been thrust up in the central part of the lava field enclosed by the greater vulcanoids. In character of summits and slopes these tumefactions of the ring plains are to my seeing essentially like the so-called mountains. They often attain to near the average height of the peaks in the Alps or the Apennines or other lunar fields of crowded elevations. The facts have led me to the following considerations and to a working hypothesis based on them :

Noting that the peaks formed in the central part of the lava floors of the greater vulcanoids clearly indicate that, after a period when tolerably fluid lavas existed beneath the crust, there came a time when these lavas were so viscous that while they might be extruded they would not flow, but retained the shape in which they were spewed out ; noting also that the evidence from the invasion of the vulcanoids by mountain ridges indicates that these elevations were among the more recently formed structures of the maria, we are led to the suggestion that they represent a stage of the eruption when the ejected materials were so viscous that they could no longer form vulcanoids, but poured forth masses which not only did not flow but heaped up near the vent, just as they evidently did in the central field of many craters. It is true that small craters are here and there, though rarely, found amid these mountainous elevations ; they may represent the localized remnants of the once general fluid state, remnants sufficient to produce slight eruptions of the earlier type.

I have already called attention to the fact that the distribution of the exceedingly numerous small bleb-like domes on the lunar surface suggests that they are the first stage in the development of craters, the imprisoned vapors serving to lift the surface although it was not broken through. It appears to me likely that it is in such elevations that we have also the beginnings of the other group of vulcanoids, the ejected peaks. In several parts of the moon, notably in the region where mountainous elevations occur, these domes abound. In some cases small craters occur in the same field, which suggests, as before noted, that these bleb-like elevations may have been the first stage of such vents; in other cases the cones appear to pass by a series of transitions into the mountainous form. I have not been able to verify this passage from the dome to the peak, but the indications of it appear to me to be noteworthy. In this connection it may be remarked that the structures in the centers of the middle-sized vulcanoids lend support to the view that a dome-shaped elevation may, by further development, pass into a peak. When these prominences are low and small they often have a rather evenly arched form, but when they are of considerable magnitude they take on a complicated shape with serrate crests substantially like the structures classed as mountains, the only evident difference being that the masses are not so commonly elongate in horizontal section, as the individual mountainous ridges commonly are.

The observed facts concerning the mountainous protuberances of the lunar surface lead me to the opinion that they are classifiable in one group, of which the simplest and most interpretable examples are found in such peaks on vulcanoid lava plains as that of Theophilus, where we have a mass of ejected materials which shows no trace of flowing for it has very steep walls. (See plate XVII.) This great viscid ejection covers an area of more than three hundred square miles, and rises to a height of six or seven thousand feet above the floor of the crater; it is particularly interesting for the reason that while it is essentially a group of peaks it retains traces of what seems to be a volcanic type, as it has an indistinct crater on the summit of the mass. Other instances could be cited to show this passage from the conditions of a crateriform structure to a rugged cone. In fact the series appears to be sufficiently fairly complete to establish the point that the last stage of activity in the craters of the vulcanoids was that in which the interior lavas, primarily hot enough to flow in the manner necessary to form very level surfaces, had become so viscous that they would maintain themselves at angles of sixty degrees or more to the horizontal.

As for the ejections of viscous lava which took place outside of the craters, forming mountain-like elevations, the evidence appears to warrant the conclusion that they represent, as do the craterless cones within the rings, a survival of a tendency to eruptions after the time when the lava was liquid enough to produce the normal vulcanoid structures. In these later eruptions, because of this exceeding viscosity of the ejected material, there could be no ring wall or interior lava plain formed. All the material which would have gone to such constructions was heaped in the viscid mass which was forced out of the opening. The natural result of these conditions is that the mountainous elevations, while less in diameter than the larger vulcanoids and having no more material than goes to the formation of an ordinary lunar cone and lava plain, present normally very elevated peaks.

It may seem that if the craters and the mountains are the result of essentially the same expulsive energy, with no other difference in the conditions than the suggested variation in the fluidity of the lavas, we should find a series of intermediate forms between the crater and the peak. Such intermediate stages are, as I have noted, to be found in the central structures of the normal vulcanoids. I have here and there suspected like transitional shapes among the mountains, but can cite none that is conclusive. There are, however, in the region of the Alps and other fields in the northern hemisphere of the moon various instances which may be of this nature. My eyes are no longer fit for such difficult observations, so I must leave this point, along with many others, unverified. It is well, however, to note that the passage from the state in which the lava of the moon's interior was sufficiently fluid to bring about the formation of the ordinary vulcanoids, to that in which peaks only would be formed, does not involve any great change of temperature. In terrestrial conditions, a lowering of a few degrees in heat at the critical point in a progressive cooling would be sufficient to bring about the change in the nature of the eruption.

The frequently elongate shape of an individual mountain seems at first sight to be, and perhaps really is, an objection to the above-described theory of their origin. It is, however, to be remarked that a large part of these elevations have rudely circular bases, and that where they depart from this figure they do not take the shape of long, continuous ridges, the major axis rarely exceeding the minor in the ratio of more than two to one ; moreover, some of the mountains of the crater floors show the same tendency to elongation. Later on in this writing I shall note that the phenomena of "rills" and other rifts show that the surface of the moon was very generally in a state of contractile tension, and this before the formation of the smaller vulcanoids was arrested, and further that the axis of the mountains often coincides with the direction of the rill-splitting. If this be the case, then the extrusion of somewhat rigid materials such as formed these cones would naturally tend to rend the crust as with a wedge, so that an elongated opening would be formed for the extruded mass and the shape of such opening would determine the outline of the elevation.

There is yet another class of reliefs on the lunar surface, those which are typified by the great escarpment of the Altai Mountains in the fourth quadrant. (See plate XVI.) In this Altai relief we find in the southeast a slight and gentle rise of a field, which has few very noteworthy features, for a hundred miles or more to the edge of the steep, and then a sudden fall to the northwest, the descent being on the average at least six thousand feet. The crest of this declivity is much varied ; one peak, at least, is said to attain the height of thirteen thousand feet above its base. It appears likely that the northwest face of the Hæmus Mountains and the southeast face of the somewhat similar district lying between Eratosthenes and Mt. Hadley, facing the Mare Imbrium, are structures of a related nature. The most warrantable hypothesis, from the point of view of the geologist, is that these reliefs are due to faulting on a large scale, accompanied by a considerable amount of extrusion of the type that forms lunar peaks. In two of the three evident examples of this group, those last named, the lava of the maria has extended to the base of the declivity ; in the case of the Altai steep, the igneous matter of the Mare Crisium, though it once extended much beyond its present limits, did not attain the base of the escarpment. There are divers other steeps which may be allied to those above described; of these perhaps the most interesting is that which forms the border of the Sinus Iridum and of the Mare Imbrium, to the northwest and southeast of that remarkable bay; nearly the whole eastern shore of the Sinus Roris and of the Oceanus Procellarum may be of this nature. Though the last-named escarpment does not rise suddenly to any great height above the mare plain, the straightness of the line suggests that it was originally of greater vertical extent and was formed by faulting.

The principal objection to the hypothesis above stated, that the above-described features are due to faulting, is found in the fact that clear instances of such action are rare on the lunar surface. The most conspicuous fault, where there can be no doubt as to the nature of the conditions, is that commonly known as the Strait Wall on the surface of the mare between Birt and Thibet. (See plate XXI.) Here the break has a length of at least sixty-five miles and is quite as rectilinear as any terrestrial fault. The vertical dislocation is at least five hundred feet and may be much greater. It is evident that this is relatively a modern feature, having been formed after the time when the mare had cooled. It is not unlikely that in the earlier ages, when the moon was parting more freely with its heat, the resulting faults were of far greater extent than is shown in the Strait Wall. It is to be noted that the break of the Strait Wall did not lead to the extrusion of any considerable amount of igneous matter. Elger has observed craterlets and mounds upon the crest of the escarpment, but it is not clear that these are genetically connected with the break, for such features abound in the Mare Nubium as in other seas. Thus, though there is no basis for certainty, I am disposed to regard the Altai group of escarpments as due to faulting.

As to the age of the great escarpments above described, it may be said that they certainly antedate the maria, which have their margins to some extent determined by them. They seem also to antedate some of the larger vulcanoids, for Piccolomini, which is about sixty miles in diameter, being in size among the score of greatest structures, was formed after the Altai escarpment. Plato also, though less clearly, appears to have been formed after the steep which bounded the Alps on the south, now somewhat effaced by the Mare Imbrium, was developed. If this hypothesis, which seeks to account for the steep faces of highlands by faulting, be correct, we must regard these features as among the most ancient, perhaps the very oldest, reliefs on the lunar surface. They are now to a great extent masked by the maria, which have found in them their natural shores, they being, it would appear, bordered by them for near half their total coast line. Further reference to these features will be made in the discussion of orogenic action.

VALLEYS, RIFTS, AND RILLS.

In addition to the above-described positive reliefs of the moon, the surface of that body presents a multitude of minor depressions which demand consideration; of these the most notable are the cavities which have received the obscurely defined name of valleys. The most conspicuous depression ordinarily classed in this group is the great Alpine valley which traverses the mountainous ranges of that name, extending in a northeast direction from near the Mare Frigoris to the Mare Imbrium, a distance of about eighty miles. (See plate XXIII.) In width it varies from four to six miles, but at its southern extremity for about one-fourth of its length it is somewhat narrower, being reduced at one point to about two miles in cross-section, and at the mouth it is beset with what seem to be extruded masses, so that it debouches by several narrow clefts into the neighboring sea. The walls of this valley are generally nearly vertical; from my own comparisons with other measured objects, they appear to average more than a mile in height and to be for the greater part of their extent almost rectilinear. The floor of the depression is approximately level, though with some obscure pits, and by its color as well as its form is evidently covered by an extension of the Mare Imbrium. The Ukert valley, on the east side of the crater of that name, is longer than the Alpine and has about the same width with less depth. The fracture by which it was formed appears to be continued in an obscure cleft, which extends from its northern end to the vicinity of the vulcanoid called Marco Polo, the whole constituting what seems to be one structure nearly two hundred miles in length. A similar valley with a length of about eighty miles lies on the west side of Herschel. It has a width of at least ten miles and is rather straight-walled. Yet another notable feature of this group is that lying on the eastern side of Rheita, which is about one hundred miles in length and about twelve miles in diameter. Last of all we may cite the great valley on the southwest side of Reichenbach, which extends in a rather tortuous course for about one hundred miles and has a width of ten or twelve miles. There are many other similar, though smaller, valleys, varying from a maximum width of ten or twelve miles downwards, until they grade in dimensions into the group of clefts. A full list of these structures is lacking, but they probably number several score.

As regards the distribution of the fault valleys, it is noteworthy that all the distinct examples of the group lie outside of the maria. It is true that on those fields there are depressions which have been classed with the vales, but, so far as I have been able to determine, they all fail to exhibit the essential features of this group—*i. e.*, they lack the steep walls and the generally rather level floors characteristic of the true valleys. They seem to my eye to be in their nature synclines, or downward foldings, the counterparts of the continuous ridges which are so characteristic of the maria, though they are not found in any definite relations to those up-folds. As to the time of the formation of the valleys, it appears to have been relatively late, posterior to the formation of the mountains, though before the production of the lavas of the maria. It is not certain that any larger vulcanoids than the craterlets were formed at a later stage in the evolution of the surface, for only very small structures of this group appear to have been produced in their cavities. It is also to be noted that these fault valleys are most developed in the regions where the larger vulcanoids are not very abundant, though it must be said that they are not lacking in the fields where these features are well developed.

CRATER VALLEYS.

In this group may be placed a number of curious though unnoted structures in which one or more craters have been in some way deformed so as to make a broad valley. The range of this action is great and the features to which it gives rise rather obscure. The changes of shape, arising from this deforming action, become very difficult to observe in all the vulcanoids at any distance from the central field of the lunar surface, for the actual elongation is confused with the apparent lengthening of the basins brought about by the obliquity of the view.

A fair sample of the crater-valley type is found in Hypatia, in the north-central part of the fourth quadrant. (See plate XVII.) Here the crater is so far deformed that its major axis, extending in a S. W.–N. E. direction, is about twice as long as its minor axis; moreover, this depression is vaguely continued as a valley for some distance beyond the walls of the crater. There are other like depressions in this neighborhood. Gutemberg in the same quadrant passes on the south into a broad, extensive, ill-defined valley. Palitzch, near the western limb, is a yet more characteristic sample, having, according to Elger, whose reckonings appear always to be accurate, a length of sixty miles and a width of only twenty miles. Capella also exhibits this passage into a valley, and there are, according to my notes, six other like instances in this part of the field. It would be possible to collect not fewer than one hundred instances of the deformation of craters into elongate valleys, or their extension into broad vales, which are in some way evidently connected with them. As I am not undertaking a list of lunar features I cite only such as are needed for illustration of this point.

Besides these numerous cases, in which the craters have been so far deformed that they have had the character of valleys imposed upon them, there are about as numerous instances in which the greater vulcanoids have been but slightly deformed—so little changed, indeed, that the alteration has escaped observation. In these cases, which include a large part of the pits over twenty miles in diameter, the northern and southern walls show a distinct, though often slight, change of form, indicating an elongation in that axis. I find that in my rough notes of observations I have termed this the "spooning" of the crater in that meridional direction. This feature may be best noted in the vulcanoids of the central part of the lunar surface. It is distinct in Hipparchus and Albatagnius which approach being crater valleys. Alphonsus and Davy show the same feature, and it may be noted in perhaps one-third of the greater vulcanoids which are so placed as to make it possible to discern this feature in its slightest expression. (See plate XVIII.) Without at present undertaking to discuss the condition which has brought about the evident warping of these greater vulcanoids on the meridional line, it may be said that its aspect suggests that they have been involved in certain movements, tending to produce considerable synclines. I have sought for, but failed to find, clear evidence of anticlinal folds corresponding to these troughs, yet the inquiry has not been carried far enough to insure that they do not exist.

CLEFTS AND RILLS.

The clefts and rills of the lunar surface are features which seem to me to belong in one group, though they may reasonably be separated from one another by certain differences. Among the clefts we may class the very numerous rifts which intersect the walls of the vulcanoids, particularly those of larger size, which often extend for considerable distances beyond the limits of the ramparts in which they occur. In the characteristic examples of this group, the features radiate from the crater, and are thus shown to be in some way connected with its conditions. They closely correspond in appearance with the Val del Bove on the eastern versant of Ætna and many like structures on other terrestrial volcanoes. In some cases they appear to be essentially akin to the terrestrial *Graben* or multiple fault depressions, as for instance the Alpine valley, in that the ground between two fractures has been lowered. They may, indeed, be regarded as a variety of that class of depressions determined by the strains originating in a vulcanoid. There are very many examples of the group, ranging from those which produce broad breaches in the crater walls to such as are shown on the flank of Tycho, where the two parallel light streaks, which appear to follow the path of faults, have the ground between them apparently somewhat lowered, in the manner of a rather gentle syncline, without any evident displacement.

Related to the several fault groups of depressions in that they are alike the results of fracturing of the crust are the remarkable features known as rills. In this group we have a single fracture with a space separating the walls, but no distinct indications of a floor between them. Perhaps the most characteristic example of the group is that known as the Sirsalis Rill, so named because the Sirsalis vulcanoid lies near to it. Elger's description of this structure — he evidently knows it well — is as follows : "Commencing at a minute crater on the north of it [= Sirsalis], it grazes the foot of the Glacis, then passing a pair of small overlapping craters (resembling Sirsalis and its companion in miniature), it runs through a very rugged country to a ring plain east of De Vico [De Vico *a*] which it traverses, and still following a southerly course, extends toward Byrgius, in the neighborhood of which it is apparently lost at a ridge, though Schmidt and Gandilot have traced it still farther in the same direction. It is at least three hundred miles in length and varies much in width and character, consisting in places of distinct crater rows." It has been suggested, according to Elger, who does not state by whom, that the rills are not in fact breaks but a series of small craters so near to one another that the effect on the eye is that of a continuous crevice. This view, according to my observations with the excellent fifteen-inch Mertz refractor of Harvard University, is not maintainable ; while craterlets are often present along the line of the rill, their nature as fractures, when clearly seen, appears certain. The breaks are ragged, as if torn through a row of craterlets, not usually more than half a mile in diameter and often narrowing at one or both ends, so that their terminations cannot be determined ; but that they are in their essence rents seems to me beyond doubt.

As regards the number of the rill fissures on the visible part of the moon we have no good evidence. They are probably to be numbered by thousands, and as the fainter seem to be the more plentiful, more effective instruments may reveal many thousands of them. As regards their distribution there are many noteworthy features. First we observe that those which have been mapped show an obvious tendency to be arranged in groups, and in these groups the individual breaks show here and there a tendency to intersect one another, though they are more often arranged in a parallel relation. The next point is that those which are in appearance sufficiently conspicuous to be mapped lie mostly in the central part of the visible surface between the parallels of 30° north and south of the moon's equator, and within 30° east and 50° west of the central meridian. They are thus remarkably rare in high latitudes and apparently seldom near the east and west margins of the visible part of the sphere. This apparent feature of distribution may be due to the oblique view of those marginal fields. It is also to be noted that all the important fractures are situated on or near the maria, or on the floors of the greater vulcanoids. Of about seventeen examples mapped by Elger, twelve intersect the shores of maria, and none of them lies altogether more than one hundred miles from those lines. The great southern upland has no mapped examples and the central parts of the larger maria are also without them. I am aware that the floors of the greater vulcanoids abound in rills all of small size. I am also aware of the fact that somewhere about a thousand of these rill fractures have already been noted and that their distribution is much wider than that indicated where only the more important are plotted, yet there is probably some significance in the grouping of these greater specimens of the class in or near the maria.

As to the time of the formation of the rills, it may confidently be said that they appear to be, with the possible exception of some of the craterlets, the most recent structural features of the moon. If narrower scrutiny than has yet been given to the matter shows that craterlets have developed in the cracks, then the later structures, of course, postdate the rills. If, however, as it seems to me quite possible, the rills have merely followed lines of incipient fracture, such as joint planes would afford, in some instances going around the pits instead of cutting through them, the rills may be the very last of the considerable lunar accidents. Such, indeed, they seem to me to be.

OROGENIC ACTION.—CAUSES OF DISLOCATIONS.

We turn now to consider the possible causes of the dislocations on the lunar surface which are represented by the various kinds of valleys, clefts, rills, and ridges which have been briefly described above. First, as to the valleys of the Alpine type, it may be said that they appear to correspond to the *Graben* type of terrestrial down-faultings, where there are two or more approximately parallel faults, the included area having been lowered. As to the origin of geological *Graben*, we have as yet no evidence of value and naturally no consensus of opinion.

It appears, however, most probable that they are due to the orogenic strains which enter into the complex of actions involved in mountain building, combined with some withdrawal of support ordinarily afforded by the materials of the under earth, as would be brought about by the migration of matter seeking volcanic vents. In the simpler and more applicable case of these down-faulted blocks of the crust, such as occasionally occur about terrestrial volcanoes, we may fairly assume that the sinking was due to the ejections which had made the under earth unable to support the load. That such deficiencies of support would have locally resulted from the lunar eruptions is highly probable. To this action then, with fair probability of its truth, we may for the present refer the valleys of the Alpine type. The minor cleft valleys radiating from the vulcanoids are evidently to be most reasonably explained on the same hypothesis. They are, indeed, so far as I can see, comparable to the Val del Bove of Ætna.

The rills, where we have relatively narrow crevices, which seem to extend indefinitely downward, with no distinct floors, may be regarded as due to the secular refrigeration of the superficial parts of the lunar sphere at a time so late that they found their way to no bodies of lava. They are evidently contraction cracks formed on a very extensive scale. Where they are limited, as is often the case with the smaller of them, to the lava field of a large vulcanoid, they may represent no more than the contraction of that body of lava. When, however, they are on the maria, an indefinitely extended sheet of the frozen material may find relief in the fracture. The predominance of the greater rills on and about the maria may be due to the fact that, whatever was the origin of those vast bodies of once igneously fluid rock, the consequence of their appearance on the moon's surface was, when they cooled, a great necessity for contraction. Not only were the lavas of the maria originally at a high temperature, but they must have communicated this heat to their shores and to the high country near them, with the result that new and extensive readjustments due to cooling would be required in those portions of the crust which had been thus affected. Thus the rills and the Alpine valleys appear to be distinctly diverse in origin, the former being due to loss of temperature of the crust in general, the latter to more complicated action.

As regards the rare instances of true displacement faults such as the Strait Wall, they appear to be due to ordinary faulting such as so abundantly occurs on the earth. They may in their first stage have been rills where there was some lack of support which caused the rocks on one side of the fracture to change their level with reference to those on the other. The only peculiar feature about them, from the point of view of geology, is that they are so rare and apparently so unconnected with compressive strains. If the surface of the earth as it has been affected by faulting, but without the effects of erosion, could be examined under the conditions in which we behold the moon, the fault dislocations would appear by the hundred thousand and with vertical displacements of miles in height. Nothing, indeed, so well illustrates the very great difference in the history of these two neighboring spheres, the moon and the earth, as the diversity in the development of this group of structures which they exhibit.

The next question is as to the group of lunar reliefs to which the continuous ridges of the maria belong. It seems clear that, whatever be the detailed structure of these ridges, they indicate compressive actions of the terrestrial mountain-building type. The great linear extent of these compression ruptures shows that they are due to no local strains but are the result of stresses which pervaded wide fields of the maria. Their narrowness and lack of considerable height may be taken as evidence that they are the result not of deep stresses but of such as resided in the superficial parts of the crust, probably within the lava of which these fields are composed. As to their age they of course postdate the formation of the maria and apparently the larger vulcanoids — none, indeed, of great extent — which have developed on their plains. It is obviously important to determine the time of their uplifting in relation to that when the rills were formed. This I have been unable to do in a satisfactory manner. I have no notes of good examples in which either of these groups of structures are found in intersection; nor does my limited acquaintance with the literature of the subject supply such instances. It appears, however, likely from the fresh aspect of both groups of dislocations that they are not of very diverse age, but that the rills are the newer.

The problem presented to us is the existence in the same field of the rills which indicate the shrinkage of the material of which the maria are composed, together with that of the continuous ridges which even as clearly show that this portion of the moon's surface has been in a state of compression that compelled the rocks to buckle upwards and, if we have rightly interpreted the structures, brought about the formation of corresponding synclinal forms, the shallow troughs which exist on these plains. If it is proved, as seems likely to be the case, that the rills on the maria were formed after the continuous ridges, then we might conceive that the cooling of the interior of the moon brought about a compressive strain on the already cold outer crust, and that the limited diameter of those wrinkles was due to the fact that there was still some measure of viscosity in the lower part of the lavas of the maria which made it possible for the hard upper part of the sheet to act independently of the subjacent portions of the section, so that this upper part of the sheet as a whole received the compressive stress as a thrust from the shores against which it lay.

There is another way in which we may consider this problem of associated compression and shrinkage in the maria. It is to be noted that the most distinct examples of each action lie in fields remote from each other, the rills near the shores and the continuous ridges remote from them, the one in fields where the lava is presumably rather shallow, the others where it is deep. With this difference in conditions it might come about that contraction of the deeper parts of the marial sheet in the process of cooling would be sufficiently strong to fold the surface, while in the quickly-cooling shallow parts of the maria the only effect would be the formation of shrinkage cracks. It is to be noted that something like these diversities of action is to be seen in terrestrial lava fields, though it is not certain that they are due to like causes. On any frozen expanse of lava we are apt to find at once ridges which cannot well be attributed to the *roping* of the solidified crust, along with cracks which are evidently due to superficial cooling. There are other possible explanations of these contracted dislocations of the maria, but I shall here take leave of the subject, for it is one on which I have not been able to form a satisfactory opinion.

ADJUSTMENTS OF THE SURFACE TO CONTRACTION.

Looking over the whole of the lunar structures, the geologist is naturally surprised to find so little in the way of adjustment of the crust of the sphere to a nucleus diminished by the loss of heat. On the earth he sees in the ample folds of the sea-basins and of the continents, as well as in very many folded mountain chains, what he takes to be evidence of a long-continued accommodation of an anciently cooled crust to a central mass which is ever losing heat. On the moon he finds what, in proportion to the size of that sphere, is surely not the hundredth part of such action. The folding of the marial ridges and furrows is trifling and is probably due to action set up in the lavas of those fields. The features of the crater valleys and the deformed vulcanoids appear to indicate some small measure of folding, but that may have been brought about by the loss of the moon's rotation through tidal action, and the consequent disappearance of an equatorial bulging due to that rotation. In any event it does not appear to represent any considerable readjustment of the crust to the interior. It is true that the moon has only one-fourth the earth's diameter, and the folding caused by shrinkage should only be in about that ratio to like action on the earth. Yet on the satellite the process of cooling is probably at an end, while in the case of the earth, reckoning from the time when the crust was formed, it cannot well be more than half accomplished. What then is the meaning of this startling diversity in the orogenic history of the two spheres?

In considering the difficult problem which has been just above suggested, the first question that comes before us is as to the value of the evidence concerning the antiquity of the general surface of the moon. We may ask whether the original sphere may not have cooled in its time to a low temperature, making in the process the necessary adjustments of its outer crust to the diminished interior, and whether after that was all done the mass may not have been added to by the in-falling of meteoric bodies. such as has been hypothesized to account for the maria. By such in-fallings a general outer coating of lava might have been formed, only a few-score miles in thickness, and to this may be due all the vulcanoid phenomena down to the time when the later coming of other such bodies formed the maria. On the basis of this conjecture we would not have to look for any extensive marks of readjustment of crust to central mass. It cannot be denied that the body of any celestial sphere is liable to be added to by in-falling masses, at least until it has cleared its path of them ; and the fact that it has been found necessary to account for the maria by such action lends a certain countenance to this view. Yet it seems to me safer to suppose that the moon has, as a whole, had essentially the same experience in space as our earth. As before noted, the earth, since its organic life, at least in the present series of forms, began to exist, has evidently had no such impacts of foreign bodies as formed the maria. It is, of course, among the possibilities that the earth has been subjected to invasions of large meteoric bodies, as the moon appears to have been, and that an ancient organic period was not only destroyed but the records of its existence entirely effaced. There is, however, no other known evidence on which to found such a conjecture, except what we find on the moon.

As regards the failure of the moon to exhibit the marks of adjustment of its crust, which first hardened, to an interior diminished by the loss of heat, it may at first appear that as the value of gravity is only about one-sixth what it is on the surface of the earth the stress which would impel the superficially cooled section to accommodate itself to the lessened bulk of the interior would be proportionately smaller, so that the outer shell might remain unsupported while the inner portion shrunk away from it. This view seems inadmissible, for the reason that in the case of the earth, as has been well reckoned, a shell less than a mile thick would, if unsupported, crush and fall in of its own weight, so that in the moon the crust would in a like manner crush at less than six miles of depth. It is thus evidently necessary to form some other hypothesis which will account for the lack of adjustment. I have essayed several of these, which I will now briefly set forth with the reasons why they seem adequate or otherwise.

At first it seemed possible that the aggregate wrinkling and crushing exhibited in the larger ridges and furrows, as well as in the host of small ridges which are seen with the greater telescopes, might have been sufficient to provide for the necessary contraction through the buckling and shoving of the crust. Yet on carefully examining selected areas of the crust where these features are best shown it does not seem possible that the accommodation or "take up" thus effected can amount to many miles of length. Moreover, the phenomena are not those which would be produced by the folding of a thick crust, as it sank upon a diminished nucleus, but only such as superficial strains would induce on a thin outer layer. It appeared conceivable that for some reason an accommodative folding might have taken place on the portion of the moon which is never seen, but this supposition is supported by no evidence whatever; all we see on the extreme margin of the visible surface leads to the conclusion that the hidden side is essentially like that we behold. Again, it appeared possible that the whole mass of the satellite remained in the boiling condition until it had been brought to a state where the cooling quickly induced rigidity throughout the sphere, all parts down to the center having attained somewhere near the same temperature. In this way we could explain the small amount of internal contraction which has apparently occurred since the most ancient features on the lunar surface, the larger vulcanoids, were formed.

Although in a general way we know the law of cooling bodies, we are not yet certain as to their application to celestial spheres. It is, however, evident that the earth did not cool down to anything like an equal temperature throughout this sphere before a crust was formed. But in the lighter mass of the moon, when gravity tended less to promote interior solidity than it has probably done in the case of the earth, it is possible that boiling went on so long and effectively that when it ceased the whole was at a temperature not much above the heat of lava, so that the further cooling would be uniform, and the undiminished crust would not have in any considerable measure to conform to the diminished interior. There are difficulties with this hypothesis, as with the others which have been suggested. If we could suppose that the moon had been during its cooling stage deeply wrapped with a vaporous envelope, as was probably the case with our earth at the corresponding stage of its development, it would be easier to conceive a process of slow cooling which would permit the exterior part to attain about the same temperature as the central portion, so that they would solidify at the same time. But it is likely, for reasons given below, that through its whole history as a sphere it has lacked such a covering and has been exposed to the temperature of space. Yet for all these objections it appears probable that the hypothesis last above suggested is the most tenable, and that the greater part or possibly the whole mass of our satellite became solidified at nearly the same time and at nearly the same temperature.

To the geologist, the action of the lunar surface under the limited compressive stresses to which it appears to have been subjected is of especial interest, because it shows clearly that rocks, which certainly are not stratified, apparently may warp into rather sharp up-and-down folds. The student of the earth has come to recognize that, in a limited way, foldings may take place in crystalline rocks where there is no stratification on which the separate parts of the mass may slip, nor even schistose planes that may facilitate such action, but that such extensive and far-reaching movements as are apparently shown in the continuous ridges and furrows of the maria or in the crater valleys may occur, has not been appreciated. So, too, the lunar phenomena suggest to the geologist that the variations in the action of a sphere under conditions other than those now existing on this planet may be exceedingly great.

DIVERSITIES IN HUE ON THE LUNAR SURFACE.

Under this head I shall consider the differences in the amount of light and its color which the surface of the moon sends to us, taking first the permanent hue of its several parts and then the variations which occur in the various angles of illumination. Beginning with the observations of Sir John Herschel at the Cape of Good Hope, there have been a number of studies on the light of the moon. Herschel, by comparing the color of the moon with that of the face of Table Mountain, came to the conclusion that the hue of the satellite did not perceptibly differ from that of weathered sandstone; that it was rather a dark than a bright object. It is easy to make an equivalent observation when the old moon is seen in the day-lit sky. The evidence, in a word, goes to show that the surface of the moon is, as a whole, quite as dark as the average lavas of the earth's surface when they are lit by a vertical sun.

Although the moon's surface, taken as a whole, must, according to Zöllner, be regarded as nearer black than white, there is little doubt that parts of it under certain conditions of illumination are as white as any portions of the earth's surface; as white as the chalk cliffs of Dover, probably; or as white as new-fallen snow would appear to an observer looking upon it from the moon. Although the range in the scale of tint between black and white is probably nearly as great on the moon as upon the earth, it is most noteworthy that there is no distinct trace of the other colors so abundantly exhibited in the terrestrial minerals and rocks. There are no greens or yellows, and it may be doubted if there is any trace of red. Schröter, whose scale of hues ranges from the black shadows to the whitest illuminated objects in the moon, selects ten gradations in that scale, but makes no provision for the prismatic colors; he evidently did not find them. I have a fair sense of color and have only to confirm this judgment. The geological importance of this point is considerable, for it clearly indicates uniformity in the lithological composition of the moon, or at least in the aspect of its rocks, which differs widely from that we have on the earth. It appears to me that the value of this uniformity in the color scale of our satellite may fairly be set forth as follows:

It is a reasonable supposition that the chemical elements of which the moon is composed are essentially like those of the earth, for such identities are indicated by the spectroscope in the sun and the remoter stars. It is, indeed, altogether likely that all the elements of the terrestrial rocks would be found in those upon the lunar surface. Is there any reason why they should not present us with a like range of color? It seems not improbable that this difference may be due to the lack of water or air on the satellite. In the terrestrial rocks almost all the prismatic colors are due to processes of oxidation which water brings about. Those which are thrown out by volcanoes commonly are without such hues, and only exhibit them when they have been subjected to oxidation on the surface. So subjected, they acquire, by that process acting on various substances, particularly on the iron they contain, a considerable variety of tint, including yellows, blues, and reds. Thus it seems to me the lack of color range on the moon confirms the supposition that there neither is nor has been water or free oxygen on its surface.

Within the range of tints recognizable on the moon we have room for something like as ample a scope of petrographic variation as may be supposed in the varied volcanic rocks of the earth if they were precluded of oxidation. According to Proctor, the darker parts of the lunar surface are of the tint which would be reflected by dark syenite. The whiter are probably as bright as the lightest of our volcanic rocks or the encrustations formed by solfataric action. In a word, there is no reason to suppose that the lunar volcanic rocks are any less varied than are those that come from the depths of the earth. As before noted, however, there is a striking difference in the behavior of lunar and terrestrial lavas; the lunar, except in the maria, where the evidence of high and continued liquidity seems to me plain, appear to have become stiff almost as soon as they escaped from their craters, a fact which may be accounted for by their viscidity or perhaps by the swift cooling to which they were exposed on the airless sphere.

It is noteworthy that the most important differences of hue on the lunar surface are found in the maria and certain of the greater vulcanoids. The maria are without exception much darker than the higher ground. The lavas within the craters are likewise rather dark, but less conspicuously so; but in the case of certain of the great rings near the eastern limb, notably Grimaldi, they are quite as somber hued as any of the seas. In the neighboring vulcanoid, Riccoli, there is a patch on the floor which is perhaps the darkest-colored of any part of the lunar surface. If these dark lavas were altogether peculiar to the maria, it would be easy to account for their color by the supposition that the material imported by the bolides, which I have supposed to have caused their formation, was of a different constitution from the materials of which the general surface of the moon is composed. The frequent incoming to the earth of considerable meteoric masses, composed in large part of iron, would warrant the hypothesis that the bolides which produced the lavas of the maria were largely made up of this metal. Even if not the tenth part of the lavas were of this foreign material, it might serve to effect the darkening of the resulting sheet. The occurrence of a like hue in lavas which lie on the central floors of distinct vulcanoids appears to negative this supposition.

Although for the reasons given above I cannot at present strongly maintain the hypothesis that the hue of the seas is due to the color-producing action of the bolides which produced them, it is perhaps hasty to dismiss the view without some consideration. It may be urged that the in-falling bodies were probably of varied sizes. Thus the mass or masses which I have supposed to have produced the isolated Mare Crisium were probably smaller than the mass or masses which brought about the formation of the great system of connected maria. It is fairly supposable that a fragment large enough to have given the lava of Grimaldi its peculiar hue fell within that vulcanoid, and that a small fragment likewise affected a part of the floor of Riccoli. So numerous and crowded are these great vulcanoids near the eastern limb of the moon that there is more than an even chance that two such falls would both lodge within some of them and not in the intervening country. As before noted, Plato and other less conspicuous vulcanoids situated near the maria have dark floors, but in these cases there is a fair chance that the external bodies of lava may, while fluid, have penetrated into their enclosures; its evident exceeding fluidity would probably enable it to burrow its way in, though the more viscid lavas of the craters in no case appear to have been able to flow out through the cones.

Thus while the facts do not warrant us in concluding that the color of the lavas in the maria is due to mineral peculiarities imported by bolides which formed them, it strongly suggests that explanation. Progress towards an interpretation of this point may possibly be made by a careful study of sundry parts of the lunar surface where outside of the vulcanoids there are features which may have to be accounted for on the hypothesis of meteoric falls — of masses great enough to produce some local melting but not sufficient to create distinct maria.

AREAS OF VARIABLE HUE.

Of all the diversities of hue observable in the lunar surface, those which vary from time to time are the most curious and the most baffling to the inquiry. The objects of this class may conveniently be divided into two groups, of which the first should include the irregular patches of light generally capping the flanks and ramparts of the vulcanoids and the cones they enclose, together with the bands of light color which in most instances radiate from vulcanoids or originate near them. It is characteristic of the objects in this group that they are invisible or nearly so when the sun is just rising on them, that they commonly are not noticeable, indeed, until the sun is high, and that they disappear when the illumination becomes again very oblique. The other group contains sundry examples where the fields are lighter colored in low than in high illumination, in this regard reversing the conditions of the first named series. There are no features on the moon's surface which have been the subject of more inquiry, though mostly of a discursive kind, than the first-named group of colored areas. The hypotheses and speculations concerning them have been numerous, but have led to no accepted judgment concerning them. It appears to me that the best way to approach the problem they afford is that indicated below.

First let us note that by far the greater area of the fields, which suddenly become very white as the lunar day advances, lies on the higher part of the vulcanoids, on their slopes and the summits of their enclosed cones. It is evident, therefore, that the whiteness is most likely due to some quality of the surface imparted by the vulcanoid action to which these regions have been exposed, a quality which is developed only under a rather high sun. Under these conditions the measure of whiteness is roughly proportional to the approach of the illumination to verticality, perhaps not absolutely so, for it is held by most observers that probably the brightest point on the moon's surface is the central peak of Aristarchus which lies about twenty-three degrees south of the equator. I am inclined, however, to believe that the apparent extreme brightness of this object is due to the contrast afforded by the dusky fields of the mare in which it lies, and that the fields of extremest lucency are all nearer the central part of the moon.

That the brightness of the very shiny parts of the moon, the patches and the rays alike, is not due to any change in their constitution brought about by the action of the sun during the monthly fourteen days of illumination, is proved by the fact that these features distinctly appear on the moon's surface when, in its newest stage, it is receiving a like vertical earth-light. I noted this fact many years ago, though I did not then perceive its full significance. I am now assured that my observations were trustworthy for the reason that negatives of the dark part of the new moon taken in the earth-light clearly show these differences of hue; they are, indeed, plain enough to enable one to map the more brilliant rays of the Tycho system. We may therefore dismiss the idea that these features are evolved in the progress of one lunar day to be reconstructed in the next, and regard them as permanencies made visible when they may reflect to us the light which comes to them at a high angle.

As to the conditions which bring about the large amount of reflection under a high sun from those parts of the moon which appear very white when it is full, the experience of geologists suggests the following working hypothesis: First, that the bright area may be covered by an incrustation of a smooth nature such as ice or other material which forms a sheet. It cannot be frozen water, but various volcanic emanations may be conceived as forming like surfaces of glassy smoothness. Or we may suppose that some part of the material which came forth during eruptions was distributed as vapor to become crystallized on the surface. Such solfataric action is common enough in terrestrial volcanic districts; it would often be sufficient to cover extensive fields were it not for the erosive agents which scour the surface. It appears to me, however, that the suggestion of a smooth surface, such as an incrustation, is insufficient to meet the facts, for the reason that such coating could not be formed save of frozen water or of materials laid down by fluid water. With the low temperature of the moon's crust and the lack of an atmosphere, the idea of a quick crystallization of mineral substances from a vaporous state seems more consonant with the known facts.

It is possible that the sudden-coming brilliancy of the bright patches and streaks is due to the fact that these shining areas are covered with crystals which have their planes so arranged that they are prevailingly parallel with the surface on which they lie, so that they reflect their light toward the earth only when the sun is high. This hypothesis has some support in the appearance of certain steep slopes, as those of the cones in the greater vulcanoids, where the face of the cliffs may be observed to shine brightly, when the sun's rays strike them, some time before the adjacent nearly horizontal surfaces gain the intensity of light which they afterwards acquire. A close study of this matter may afford data for a determination as to the nature of the action. So far I have been able to do no more than prove that the brilliancy is due mainly to the angle of illumination, by noting that it appears in earth-shine as well as sunshine, though the brilliance of the glow on the margins of the moon suggests that there is also an element of fluorescence or other action in the phenomenon.

Although light rays distinctly appear to be connected by series with the light patches, there are certain peculiarities about the former which demand explanation. Their exceeding length and their generally slight width make them very puzzling features. It has been frequently suggested that they are due to certain dust-like emanations from the craters which have been blown by the wind which bore them and lodged in crevices or in the lee of projecting points. The current of air which bore them is conceived as produced by the gaseous emanations from the crater. This view appears to me to be ill-founded, because the volume of emitted gases required to produce a sufficient current even in a vacuum would have to be impossibly great to make such a wind at the distance of hundreds (in one instance 1700) of miles from the vent. Moreover, as W. H. Pickering has well shown, these bands do not, in all cases, point to any large crater, but in the case of the most remarkable group — that of Tycho — appear to originate not in the main vent but in certain small craterlets somewhat on one side of that opening. Moreover, as well observed by Pickering, these bands are not definitely continuous but made up of relatively short strips of bright-colored surface, each of which appears to originate in a craterlet and to fade as it extends to another in the same line, and that this arrangement probably continues to the end of each streak.

It is also to be noted that in some instances the bright rays of the moon show a tendency to be parallel, or approximately so, to one another, they being in some way causally related to rows of small vulcanoids. I have already called attention to the existence of such near approach to parallelisms in the case of the two striking examples in the Tycho system. There is another equally good example in the case of Messier, where the two streaks of this system, though slightly divergent, show an evident departure from the normal radial order. Many other instances could be cited to show that, while these bands of lighter color obviously tend to be placed in radial position with reference to a vulcanoid, they are here and there affected by some conditions which warp them from that position and force them to become parallel. This later condition is much more common in the numerous faint streaks which cannot be referred to any group radiating from a large vulcanoid. To my eye, this tendency to parallelism affects a considerable part of the rays which appear to be of the older origin.

It is obviously important to determine whether the rays of bright color on the lunar surface are due to superficial conditions alone, or whether they are the result of some action affecting the crust beneath the surface. On this point we have little information but that of a highly indicative kind. A glance at these features when they are best presented shows the observer that they extend across the irregularities of the broken country they traverse. In at least one instance, a ray emanating from the Tycho center crosses the lava plain in the bottom of another crater (Saussure) and apparently traverses the steep slopes of its wall, while another ray of this group seems to have been deflected from its normal course by the ramparts of this vulcanoid. I have personally verified the observations on the passage of this streak over the lava plain of Saussure and have, though imperfectly, traced its passage up the inner wall of the rampart. Other more skilled observers appear to have no doubt that it exists.

The facts just above noted make it evident that the light rays are not purely superficial features, but are in some way connected with the structure of the crust; from the point of view of the geologist, they have to be accounted for by supposing that they are the superficial expression of an action essentially solfataric in its nature, wherein vapors of some crystallizable substance, or substances, have passed through crevices of joint-like nature from the deeper parts of the sphere, either to form a coating on the surface about a vulcanoid, or to stain a belt of rocks on either side of the rift, so that a strip of country, perhaps a mile or more in width, extending to the top of the crust, was impregnated with the material—the deposit being perhaps more extensively accumulated on the surface.

As already noted, there is reason to suspect that, besides the large reflecting power which the materials of the largest rays possess when the sun is high, these materials have a certain fluorescent property, which causes them in some measure to store up light which is given out after the sun has passed the angle at which they begin to shine. That such is the case is indicated by the fact that the rays are visible on the limb of the moon when the sun's light is considerably more oblique than it is when they become very bright. Such a property is known to exist in many species of minerals. A close study of fluorescence may, indeed, serve to indicate the nature of the substance which sends us the light from the very shiny parts of our satellite,— that of the diffused patches as well as that of the rays.

If we accept the hypothesis that the bright parts of the moon are due to the deposition of some highly reflecting and perhaps fluorescent materials, we may proceed to derive certain important corollaries from the proposition. It is at first sight evident, from the extent of the shining fields on and about the ramparts of the greater vulcanoids, that the egress of the light-reflecting materials was there by so many paths that the resulting stains were confluent, and that the rays marked its passage in fields where the channels were rarer, though related to the same centers of vulcanoid action. It is also evident that, while these passages for vapors from within cut a few of the crater floors of lava and occasionally extend on to the maria, they appear never to originate in those areas. Moreover, the great extent of these rays, some of them exceeding one thousand miles in length, and the way in which they radiate from their several centers, are problems of no small importance.

As to the common origin of the blotches of light material on and about the vulcanoids and the rays, the series of facts leaves no good reason for doubt. The blotches generally pass outwardly by gradations into rays, the most of which are short, perhaps less than a score attaining a length of one thousand miles or more. As to the deep-seated origin of these structures, it is fairly proved by the fact that they cross irregularities of the surface, as well as by the fact that they occur along lines of craterlets. There is some reason for believing that these, the smallest of the vulcanoids, were formed along the lines of the rills, presumably before those clefts were opened. Their existence along the light rays is of itself evidence that there is some incipient breakage along their courses. It is a reasonable supposition that vapors were forcing themselves out on those lines, and that sometimes they did so with explosive energy.

The existence of incipient crevices, such as jointings arranged in a general radial order with reference to the greater vulcanoid centers and extending for very great distances, is a feature which from the point of view of the geologist is surprising. While in the case of terrestrial volcanoes it is common to find traces of a tendency of the crust to split radially so as to permit the entrance of dike-making lavas, these fractures are not known to extend for more than at most a score of miles from the vent to which they center; nor is there any observed tendency of the crust about volcanoes to become penetrated with joint-planes, having the position of those which the before-noted facts lead us to suppose exist on the moon. Before this evident lack of likeness between the two spheres is weighed, it is well to note that, while in the case of the earth all the extensive jointing of the rocks is apparent, brought about by strains due to mountain-building action, even when the beds have not been visibly dislocated it is evident that they have been jointed by the stresses; so that the fracture systems of the earth may be said to depend on an action which does not appear to have been to any considerable extent effective on the satellite.

Given a sphere in which there are no extensive strains due to the contraction of its central part and a consequent readjustment of the crust to the nucleus, which appears to be the case with the moon, it is not unlikely that a series of ruptures such as we find indicated by the rays would be formed. In such an orb, the last stage of its cooling would necessarily lead to the contraction of its outer part. Such was evidently the case in the moon, as is shown by the late formation of its valleys and rills. After this strain had become so slight that it was no longer competent to open distinct fissures, it might still have been sufficient to produce the incipient tension cracks required for the escape of vapors such as are needed to account for the light rays.

The most difficult point to explain is the radial distribution of most of the rays and the evident relation of nearly all of them to the greater vulcanoids or to craterlets situated on their flanks. This, it seems to me, may be accounted for in the way set forth below. Let us suppose that in the last stage of the expulsion of the vapors of the lunar sphere, when the formation of vulcanoids of more than about a mile in diameter was no longer possible, the crust was by its cooling brought into a state of contractile tension so that it had a tendency to break. We may then fairly assume that this tendency would be greatest in the ancient uplands, and least in the relatively new maria and in the lava floors of the vulcanoids. These fractures, or lines of weakness, for they do not seem to have been defined openings of measurable extent, would naturally—indeed necessarily—be made as radii to the large pits of the crust which plentifully occur in the higher parts of the moon. We may have visible evidence of their necessity by watching how shrinking clay splits in relation to holes made in its surface. Beginning in the field about a vulcanoid, a fissure would extend radially for a certain distance, far enough to satisfy the strain which led to its formation; if it afterwards happened, as W. H. Pickering has noted, that a body of vapor broke its way to the surface, forming a craterlet at the point remotest from its origin, then the rupture might be continued on the same line, attended by the formation of another craterlet, until the strain was again satisfied; and this process might be again and again repeated until the greatest observed extension of the ray was brought about.

Supposing rays be formed by successive developments and reliefs of cooling strains in the manner just above suggested, we find a reason for the peculiar shape of these features which Pickering has well observed. He finds that the longest of them are not strictly continuous, but that originating at a craterlet they extend for a variable distance, widening and becoming dimmer the farther from the place of origin; then at another craterlet they again begin narrow and bright, to fade and widen once more as they become remote from the opening. According to my view, the first craterlet started the fracture; near it the fissure was most passable to the vapors in question, so there the streak is narrow and bright; farther away the fissure was less open, so that the effusion had to force its way through the country rock, and so made a wider and fainter deposit of the shining material. The second craterlet developed an extension of the fracture with the same features as the first, and so on to the end of the colored belt. According to this hypothesis, we need not suppose any such mighty accident as required by the view that the ray system of Tycho was formed at once; it may have been geologic ages in developing; the end of a great ray may, indeed, have been formed very long after its beginning.

To those who are unfamiliar with the movements of homogeneous materials in the process of shrinking, it may seem unlikely that the outer part of the moon in cooling equally would tend to fracture in systems of joints arranged in radial order. A little observation on drying clay will show that slight accidents determine in very uniform materials the direction of the fractures due to strains which lead to cracking. When the pull is equal in every direction and when there are depressions on the surface, the tendency is to make these pits the center of radiating fractures. In this way, by cracks running from many centers, the general tendency to rupture is satisfied. On the visible surface of the moon there are near two-score recognizable ray systems, differing much in the distinctness and extent of their light streaks. As these systems are widely scattered, they are perhaps sufficient to have satisfied all the shrinkage strains of the crust during the time when there were still vapors seeking to pass to the surface.

As to the age when the rays were formed, it appears evident that they were not all made at or near the same time. Those of certain systems appear to cut those of other systems. Thus, according to Nicoll as quoted by R. A. Proctor, the rays of Copernicus, Aristarchus, and Kepler cut one another in an order indicating that they were formed in the succession in which they are here named. It also appears possible that the greater part of the ray systems were formed before the maria were produced, for relatively but few extend over their fields, though it may be that their general failure to traverse these bodies of lava and also those contained in the craters of the greater vulcanoids is due to some condition of the material which diminishes the shrinkage tension existing on other and older parts of the moon. That the light rays antedate certain of the rills, and perhaps all of them, is shown by the fact that they are cut by these fissures. It should, however, be noted that Trouvelot, who had a very keen eye, noted that certain of these open crevices are continued beyond the point where they are distinctly gaping by slender streaks of shining material, which appear, from his description, to be like the rays. It may be that vapors ascending through open clefts would not be sufficiently concentrated to produce a distinct band of color on their margins, while such would be the case when they mounted through an incipient fissure, as I have supposed to be the fact with the radiating streaks.

In considering the succession of the ray systems, it should be noted that, beside those which are definitely to be observed, there are evidently others in part destroyed by later developed groups. In the best conditions of seeing, these faintly indicated and evidently ancient sets of rays may be seen in all stages of obsolescence, down to the state where they are conjectured rather than observed. This, together with the phenomena of interference of one set of rays with another, suggests that the process of their formation may have been continued for a very considerable time, though the development of the larger bands appears to have been brought about only in the later state of the surface, yet, as remarked above, not to the very latest time of activity.

It is evident that the distribution of the several ray systems is not equal on all parts of the moon. Thus the first quadrant has thirteen recognized groups, while the fourth, just south of it, has but six. The second quadrant has eleven and the third eight. Thus the eastern and western halves of the surface together have the same number, but the northern hemisphere has twenty-four and the southern fourteen systems of rays. Moreover, the greater number of the groups are situated on that half of the visible surface wherein lie by far the greater part of the maria, and on the surfaces of those lava fields none of the distinct centers of radiation are found. This predominance of the rays in the regions of high country near the maria may possibly be due to the extensive heating of the northern half of the moon by the lavas which formed them, and to the consequent refrigeration which would tend to develop crevices and thus lead to the production of rays.[1]

THE PRESERVATION OF THE RAY SYSTEMS.

The facts already set forth clearly show that the ray systems are fairly to be regarded as features which have been somewhat gradually developed, and are, as a whole, of ancient origin. It is, indeed, difficult to escape the conclusion that they are, when measured in terms of geological ages, all exceedingly old. They

[1] In the earlier years of my work on the moon, the results of which are here set forth, I noted certain very faint rays which appeared to point to centers of radiation on the unseen side of the moon. I have been unable to find the note-book in which these observations were recorded, and my eyes, damaged by studies on that brilliant surface, no longer enable me to trace them. According to my memory, these streaks, as are all others near the limb, were faintly though distinctly traceable, in the course of some years' observation, to the number of about a score, indicating about half a dozen such invisible centers. The impression left upon my mind is that the very best vision and opportunity might prove the existence of at least a dozen of these groups where the rays converged to a point in the invisible field. The studies needed to determine this matter will be difficult to make, for the reason that all these rays are faint in the regions near the limb.

must be judged to be the result of actions essentially like those termed by geologists solfataric, *i. e.*, due to the escape of vapors from a heated sphere, which have colored or coated the surface on which they lie. The considerations which lead us to believe that this internal heat of the moon vanished long before the earth's surface became frozen over are very strong. Accepting the view that the light streaks on the moon are of exceeding antiquity, the question arises as to why they have not been obscured by the fall of meteoric matter upon the surface of that sphere. It is a well-known fact that some hundred thousand, if not some million, meteoric bodies come upon the earth each day. It is true that nearly all of these bodies are so small that they are burned by their friction in the atmosphere, and are added to our planet only as dust that descends in the rain or as gases contributed to the air; but on the lunar surface, which, apparently, should receive, per unit of area, quite as many of these fragments as the earth, there is not, and probably never has been, an atmosphere sufficient to decompose these wanderers so that they should have attained its surface unchanged.

Estimating the average diameter of the meteorites that come into our atmosphere at only a millimeter, which, in view of the light they afford, is probably too small, it is evident that even in a hundred thousand years they would, if gathered on the surface of an airless sphere, be sufficient to form a coating such as would give a common hue to all its features, and in a geologically brief time the mass would attain a considerable depth. Yet we have evidence in the ample gradations of light reflected from the moon that very ancient features of color are as undimmed by foreign matter as newly fallen snow. In other words, we seem to be compelled to the opinion, either that there has been no such in-falling of meteoric matter on the moon as has of late taken place on the earth, or that the whole scheme of coloring on the lunar surface has been formed within a few thousand years. That the latter of these suggestions is not true is clearly indicated by sundry considerations. It is, in the first place, to be noted that there is much to show the absence of any accumulation of fragmental matter since the oldest of the lunar features were formed. A meteoric rain such as comes upon the earth for even a million years would have masked a host of objects which, though presumably very old, are still manifestly unaffected by any such sheet of dust as would have enwrapped the lunar sphere. Thus the exemption from meteoric contributions appears to have been from a very remote time. Moreover, as before noted, the rays of different systems are of diverse ages, yet there is no indication that the newer are very much brighter than the older.

As for the other possible explanation, *i. e.*, that the moon has not long received meteoric material in the manner in which it now comes upon the earth, there appear to be at first sight but two diverse ways that may have brought about this condition. In the first place, the earth and moon alike may, until very recent times, have been exempt from such contributions. In the second place, it may be that the matter which falls on the earth is in whole or in large part limited to materials which have been ejected from the planet by volcanic action. The first of these suppositions must be regarded as possible, though rather improbable. While there is no recorded instance of any meteorite having been found in ancient geological deposits or elsewhere, save upon the surface of the earth, the rarity of falls sufficiently large to escape burning in the air makes it unlikely that they would be discovered in a fossil state, or, if found, that they would be recognized as of meteoric origin, so that this consideration has not much weight. On the other hand, if, as seems likely, the supply of carbonic dioxide in the air depends in any considerable measure on the burning in it of carbon meteorites, the presence of this material in something like its existing quantity, certainly neither much greater nor much less, from the early geologic ages, is evidence that meteoric falls, at least those containing carbon and of the smaller size, have during that time been at about the same rate as at present. So far as I can discern the astronomic conditions, it seems very improbable that the earth should now be encountering a multitude of small bodies such as had not come to it until within a few thousand years.

The suggestion that the meteoric matter which comes upon the earth may have been expelled from it, though possible, does not seem to me to afford a way of escape from our difficulty. It appears not improbable that volcanic action may be sufficiently violent to impel bodies beyond the control of the earth's attraction. The shining clouds which were observed for some years after the eruption of Krakatoa in 1883, and which went upward until they appeared to escape from the atmosphere, may be instances of this nature. Moreover, large fragments, which have been hurled forth by great eruptions, have been known to fall at such distances from the point of ejection as to make it likely that they had an initial velocity near to that which would be necessary to send them into space and to make them independent of the earth; but, if I conceive the problem rightly, such ejections would either in very rare instances fall upon the moon or proceed to move in elliptical orbits, one focus of which would be the sun and the other the place in space where the earth was at the time they separated from it. It is eminently probable that in time these fragments would be apt to return to the earth, but it seems evident that they would be about as likely to fall upon the moon.

If we had any evidence that the moon had been surrounded with a fairly dense atmosphere down to the present geological period, we might account for the absence of meteoric dust upon its surface by the supposition that the smaller bodies had been burned in its air as they are in that of the earth, but all the facts at hand, which will be discussed below, are distinctly against this supposition and in favor of the view that the low gravitative value of the sphere allows the gases which do not become solid at the low temperature which prevails there by kinetic action to move off into space; so that the development of an aërial envelope has been impossible.

I have but recently come upon the difficulties we have to face in this problem concerning the preservation of the surface of the moon from meteoric matter, and am therefore not well prepared to discuss them. As they now appear to me, they may be met by any one of the following described hypotheses: (*a*) That the meteors which burn in our atmosphere are so minute that falling at their present rate they would not have formed a dust coating had they accumulated on the surface of the earth for all recorded geologic time, and that the larger masses, such as now attain the ground, have been so rare that they would not of themselves form a coating. (*b*) That the earth and moon, as members of the solar system, and sharing in its motion through space, are now in a field where meteors are prevalent in a measure that was not the case in earlier ages, so that the moon's surface, though very ancient, has not been long enough exposed to such in-fallings to have acquired a coating of them. (*c*) That we have entirely misjudged the antiquity of the moon, and that our reckonings, based on the law of cooling bodies and on the supposition that the planet and satellite were differentiated from a common nebulous mass, are altogether erroneous. Of these suppositions, that designated as *b* seems the least objectionable, though as before noted it presents sundry difficulties.

In considering the effects arising from the fall of bodies from the celestial spaces upon the surface of the moon, we should take into account the fact that in the present airless state of that sphere they would come upon its surface at a very much greater velocity than when they break through the atmosphere of the earth. Owing to the resistance of the aërial envelope of our planet, it is doubtful if even the heavier meteorites have at the moment when they touch the ground an average velocity above a thousand feet a second. Computations which assign them a higher speed at the moment of contact are made doubtful by the slight amount of their penetration into the soil. On the other hand, the meteors which fall upon the moon must be moving at the average rate of at least twenty miles a second, or about one hundred times as rapidly. Where they impinge on the advancing side of the moon the rate would be much greater than where they come upon it from the other or following side.

The effect due to the great speed at which meteorites would usually fall upon the moon cannot be accurately determined ; certain of them can, however, within limits, fairly be conjectured. It is in the first place evident that so far as the penetration of mass into the crust was concerned it should be very much greater than on the earth. On the assumption which has been above made as to the comparative velocities, it should often be about a hundred-fold as great as on the earth. It is, however, to be noted that the increase in velocity would lead to a proportionate increase in the evolution of heat due to the friction of the penetrating mass in its passage through the materials it encountered and to the shearing of its particles on one another. Assuming the rocks of the lunar surface to have the average resistance of pumice, it seems evident that any meteoric body such as we know to fall upon the earth would not only penetrate to a great depth, but would probably be volatilized by the very high temperature it would attain. We see that a certain amount of this action occurs even in the relatively slight resistance which a meteorite encounters in passing through the air. With a resistance sufficient to produce an effective shearing movement in a meteor, such as would be encountered on entering matter of the solidity of pumice, we may fairly assume that the mass would, in effect, explode, the gaseous products being cast forth from the opening it made. The temperature produced by the arrest of the movement at a rate of twenty miles a second would vaporize the mass.

It is also evident that on a surface in the present airless condition of the moon all meteoric bodies, even the smallest, would come in contact with its rocks. As is well known, by far the greater part of the meteors which enter upon the earth are burnt in the upper air, and pass into the gaseous state or fall to the ground gently in a purely divided condition. Such bodies, however minute, would enter the moon's crust at the same speed as the larger masses. Owing, however, to their smaller bulk, they would be more quickly dissipated by the engendered heat. If this view as to the volatilization of meteors by the conversion of the energy due to their motion into heat is true, then the effect of any such meteoric fall as takes place on the earth in, say, a hundred thousand years would be to produce a mass of gaseous and dust-like material which should be somewhat widely scattered from the point of impact of each meteorite, and this for the reason that the gases evolved by the heat would enter into what is essentially a vacuum and would be radially distributed at high speed, quickly to fall upon the ground as their temperature lowered. The effect of such action would evidently be to give the lunar surface a uniform color, determined by the average light-reflecting quality of the resulting deposits of condensed vapors and dust. If, on the other hand, we assume that the material bodies penetrated into the moon without being volatilized, then the result of the first falls would be merely to pit the surface, the color being destroyed for the area of each pit, but when the successively formed pits became so numerous that they occupied the whole of the original area the color would disappear. The effect can be the better realized by firing successive charges of shot at a white plank. As the number of penetrations increases to a point where the total amount of lead is equal to a continuous layer, the original material becomes, in effect, covered with the metal and takes its hue.

The considerations just above set forth make it appear eminently probable that in either of the conditions in which we can imagine meteoric matter to have come upon the moon, that in which it was vaporized or that in which it remained solid, a period in a geological sense brief would suffice to obliterate the diversities of hue such as we find in the dark maria, the light streaks and patches, and in its general surface. Thus the best interpretation which we can give to the facts clearly leads to the supposition that our satellite has not in recent ages shared with us in anything approaching like measure the falls of detached masses from the celestial spaces.

On my first consideration of this matter I was inclined to believe that the curiously pitted or honeycombed character of the lunar surface, which becomes more and more clear as the magnifying power of the telescope is increased or the seeing more favorable, might possibly be explained by the supposition that the cavities were produced by the in-fall of meteorites of considerable size.

Many of these pits which may be seen in advantageous conditions are not more than four or five hundred feet in diameter, and seem to have the general shape that would probably be given them by the sudden effectively explosive development of gases which we have seen reason to suppose would be brought about by the penetration of large materials into the crust. Yet as there is no indication of a peculiar coloration of the fields about those pits, such as would be produced by the precipitation of the condensed vapors, this interpretation must be regarded as unverified, though it remains possible. Taking into account the fact that the best instances of the honeycomb type of pits occur in tolerably clear relation with the larger vulcanoids, it seems most likely that this group of depressions owes its origin to the escape of indigenous vapors from the depths of the lunar sphere.

The question as to the possibility of any of the distinct vulcanoids owing their formation to the impact of large meteoric bodies is elsewhere discussed. It is therefore only necessary here to note that, as the size of the in-falling body increased, the heat evolved would be augmented, so that a mass a few hundred feet in diameter would inevitably bring about such a general melting of the crust where it fell that a cavity would not be formed, but in its place a level blotch caused by the frozen lava, substantially what we find in the maria. There are, indeed, sundry patches on the lunar surface which may have this origin, but so far I have not been able to find any criteria sufficient to warrant this interpretation of them.

The eminent probability that the fall of meteoric bodies on the lunar surface should lead to the temporary production of a high temperature, suggests that it might be possible by photographic if not by eye observations to detect these collisions, if they occur with anything like the frequency per unit of area with which they come to the earth. It is possible, though not likely, that these observations might be practicable on the illuminated surface of the satellite, for the reason, elsewhere noted, that as a whole it is more nearly black than white, and even a small meteor would at its contact with the surface be likely to produce a flash sufficiently brilliant to make an impression on a sensitive plate. On the dark part of the sphere or even in a lunar eclipse it would probably be easier to make the photographic observation. It is, however, to be noted that, as meteors enter the crust at high speed and there is no atmosphere to give the train of light such as is exhibited by those of small bulk which fall upon the earth, the flash might be of very brief duration—so brief, indeed, that it might escape the eye and the camera alike.

It may well be observed that, supposing the moon's surface to have received extensive contributions of meteoric matter, we might thereby possibly explain the apparent degradation of some of its older features. On the supposition that the in-falling bodies penetrated deeply and were converted into the gaseous state so that they produced explosions, we would have an agency competent to break down reliefs in the manner in which many of the ancient features seem to have been mined. Yet when we note the exceeding sharpness of outline retained by many structures, such as the cracks, displaced faults, and the smaller vulcanoids, all of which must, on any apparently valid supposition as to the moon's history, be many million years old, we are led to believe this view inadmissible.

In this connection attention is due also to the fact that on the unilluminated part of the moon various observers have, from time to time, noted patches of light which they have believed to indicate volcanoes in activity. I have elsewhere suggested (see p. 53) that these objects may have been highly reflecting parts of the lunar surface illuminated by the earth-shine. It is barely possible, however, that in some instances they can be explained on the supposition that considerable meteorites had recently fallen at the point where the light was noted. So also it seems possible that the vapors which W. H. Pickering and others have thought they observed floating in the manner of clouds on the illuminated area may be in this way accounted for: a large meteorite penetrating deeply into the crust might give rise to vapors which would continue to pour forth for months or years after it fell. The difficulty with this hypothesis is to see how vapors could *float* and remain in the form of a cloud in the conditions of essential vacuum which exist on the surface of the moon. Granting the possibility of such action, which in the present state of our knowledge seems improbable, I should much prefer to account for these vapors by meteoric action than to seek their explanation in true volcanic activity.

EROSIVE ACTION ON THE LUNAR SURFACE.

Those who are familiar with the lunar surface as it is exhibited by a good telescope, cannot help acquiring the impression that there is some agent which has operated on the moon in a way partly to break down the more ancient topographical features. There is an evident difference of aspect between the walls of the older vulcanoids and those of newer formation. Apart from the distortions of the ancient structures and the breaches of their ramparts, which may be fairly accounted for in other ways, there are a rounding of their steeps and a general appearance of having been smoothed over by some erosive agency which are evident in proportion to their antiquity. It is indeed a general fact which has been remarked by many observers, that the newer vulcanoids have an appearance of freshness that is never found in the earliest formed. It is therefore important to discover, if we may, what are the actions by which such changes may be brought about.

On the surface of the earth there are four agents of erosion, all of which, coöperating with gravitation, serve to bring about more or less considerable changes. These are chemical alterations, which loosen the structure of rocks; the direct action of the wind, which removes their lighter particles when they are not protected by vegetation; the action of moving water by waves, streams, and glaciers; and last, and by far the least, the expansion and contraction of materials arising from changes of temperature. The essential effect of all these agents is to deliver fragments of rocks to the more or less free action of gravitation. They all act to send divided matter from higher to lower positions. Except the first and the last, they incidentally provide means of carriage by which the fragments may be conveyed to indefinite distances; chemical decay and the increase and decrease in bulk due to variable heat acting by themselves do no more than give the separated bits a chance to move down declivities of considerable slope.

It is evident that all the chemical change which occurs on the earth depends on the presence of an atmosphere containing water. This condition apparently, I think surely, does not now exist on the moon and probably, as I shall hereafter give reasons for believing, has never existed there; for this reason we may set aside this agent as a possible source of changes of lunar topography. From the same facts we are led to dismiss the possibility of wind action. The only suggestion of such work has been to explain the radial light bands on the supposition that the vapors emanating from the craters by their rapid diffusion caused winds that blew the material which forms the rays to the places it occupies. We have seen that this hypothesis does not account for the facts, and that they are apparently explained by a much simpler view of the matter.

The idea of water having been at some time in the past an agent of erosion on the moon is so persistently recurring that it is worth while to set forth, in some detail, the results of my studies of the matter. I gave over fifty nights of observing with the Harvard College Mertz refractor, which has an excellent glass, to the question of a possible aqueous history of the several divisions of the lunar field. The result was to convince me that no part of that surface, new or old, has ever been shaped by aqueous erosion, and this for the following reasons: Aqueous erosion by river action has one characteristic effect: it, in all cases, except where *pot holes* are formed by waterfalls, brings about a system of continuous down-grades from the heights to the lower ground. My inspection of the moon's surface, which, from this point of view, was carefully made, satisfied me that the streams had never done their inevitable work on that sphere; for I was unable to find a single case of a depression of considerable length having a continuous down-grade, or an instance where it might be supposed that a valley, so shaped, had been subsequently deformed. None of the rills which have been supposed to be stream-like in shape are in the least so to an eye trained in terrestrial topography. They have no gathering grounds, no trace of that digitated system of valleys which must have been formed if they had been water channels; moreover, they have a perverse habit of branching the wrong way, when they branch at all. Most selenographers have quite abandoned the idea that any of the features of the moon are due to water action, though some of them adhere to the notion that there may be some slight trace of water vapor in a supposed remnant of an atmosphere lying very near the surface.

The same arguments that exclude river action on the moon will *a fortiori* exclude glaciers. Both these forms of water require extensive evaporation areas and the machinery of an atmosphere for their maintenance. Now that it is generally accepted that the maria are not and never could have been seas, but are evidently lava fields, save in origin, essentially like those within the larger vulcanoids, there is evidently no place where waters in a sufficient extent to supply rainfall could have been stored. In this connection it is worth while to note that on the earth, with two-thirds of the surface covered with water and with air currents to carry moisture, large areas are practically unsupplied with water. Without the oceans it is evident that rainfall would cease. The little which is evaporated from the land would readily be stored in the air, perhaps to fall as dew. So that lunar rains or snows would be impossible without a system of great reservoirs, such as we cannot believe to have existed in any recorded stage of the moon's history.

There remains but one agent of erosion which can have acted on the moon, *i. e.*, that arising from the expansion and contraction of rocks in the changes of temperature which there occur. On the surface of the earth, where the average annual variation of heat on rock faces does not exceed about twenty degrees Centigrade, and where the maximum variation is probably not more than fifty degrees Centigrade, the effect of the variations is evident. Excluding, as far as we may, the concomitant influence of freezing water, we find that the expansion of rock is competent to produce cracks and to urge detached masses of rock down the slope on which they lie. Thus the concentric structure which develops near the surface in certain crystalline rocks, as granite, is due to the expansion of summer heat, which often causes the slabs of stone sensibly to lift from their beds. On the surface of the moon, according to Langley's observations, the range of temperature is probably not less than two hundred degrees Centigrade, so that the measure of expansion and contraction should be fourfold what it is on the earth. Moreover, these alterations of temperature are repeated each month. During the fourteen days' insolation, the heat should effectively penetrate for some meters of depth. Though it is doubtful if the melting point of water is ever attained, the range is as effective in promoting motion as if it occurred above that point.

The effect of the great alterations of temperature in the superficial materials of the moon is probably twofold ; in the firmly imbedded rocks it must institute successive strains and releases which should be competent to produce certain effects not recognizable on this planet. Supposing that at a depth of three meters the range of temperature was one hundred degrees Centigrade, the horizontal thrust induced, if the rock had the modules of expansion of ordinary granite, would be sufficient to produce in a sheet fifty miles in diameter an extension of some hundred feet. From what we see of like action on the surface of the earth, we are justified in supposing that sheets of great width would on the declivities of the moon become separated from the subjacent materials and move over them in the alternations of volume. So, too, we may suppose an interminable series of varying adjustments which would, from time to time, bring about alterations in the direction and energy of the thrusts which were thus induced. These changes may have continued throughout a period as long as recorded geologic time, and they may be in process of development to-day.

Another consequence of the variation in bulk of rocks in the changes of temperature of the lunar day is that fragments lying on steep slopes would slowly move down the declivities. Such detached blocks would, where they expanded and in proportion to the efficiency of the gravitative impulse, press more vigorously against the obstructions below them than on those above; they would thus gain a chance to creep farther downward when they were again expanded. This process would somewhat resemble what takes place where a talus slope is knit together by a sheet of snow ice, when we may note a creeping of the united mass due to the changes of temperature it undergoes. I have frequently observed taluses where this process has extruded the deposit, as in the manner of a glacier, far beyond the limits to which masses falling from the cliffs whence they came ever attain. This process is yet more nearly alike to that which takes place in the lead covering of roofs, where the metal has been observed slowly to work down the slopes on which it lies in a movement evidently due to alternating expansions and contractions.

At first sight it may seem that the relatively small value of gravity on the surface of the moon would limit the movement of fragments due to expansion and contraction so that the angle of repose in the taluses they formed would be very high; but on consideration it appears to me that this angle may be even lower than in terrestrial conditions, for the lessened weight of a given volume of rock would greatly diminish the amount of the friction, and the value of the adhesions which tended to resist its movements would, owing to the absence of water and chemical decay, be so slight that I see no reason why, given time enough, the talus material should not be brought to a nearly level attitude. The coefficient of expansion is likely to be the same in lunar materials as in the igneous rocks on the earth, while the resistances to such motion, both in the horizontal flakes of great width and in the detritus on steep slopes, would be but one-sixth what it is in our sphere. Therefore we may reckon on this agent of change being of greater value on the satellite than on its planet, and find in it an explanation of the worn character of the ancient topography which is not evident in the newer formations. As we shall see below, this view as to the expansion of rocks may be of value in accounting for certain possibly recurrent as well as accidental recent changes in the shape of structural features on the lunar surface which certain observations appear to indicate.

There is one rather obscure group of features on the lunar surface which may be immediately due to the expansion of the superficial materials of the crust. These are the numerous slight ridges which intersect the ground and which are fairly visible near the terminator; these ridges seem to me to be very low, perhaps not more than a score or two feet in height. They are generally rather straight-lined and so placed that they reticulate the level fields in which they lie, dividing them into irregular blocks of very variable area, rarely more than fifty miles across. I have seen what seems the miniature equivalent of this structure, where a sheet of ice on a lakelet has been affected by great changes of temperature, all below the freezing point of water, and has been broken by the expanding process into blocks which, at their contacts, are crushed up into rude little anticlinals, formed of ruptured bits of ice. These ridges of ice-fields retain their shape during the contractions of the sheet in which they lie, as the blocks of stone in the moon may do when they have found an adjustment. These lunar features deserve careful study, though the conditions make an inquiry into their nature very difficult. I have rarely been able to discern them clearly, and then for only a brief time.

ON THE POSSIBILITIES OF A LUNAR ATMOSPHERE.

The apparent arguments in favor of the existence of an atmosphere on the moon, if not now, then in some former age of that sphere, are so strong that selenologists are hardly to be undeceived by the evident facts that militate against this view. These facts are, in brief, as before noted, as follows: There is no trace of clouds on the moon; there is no difference in the clearness of the seeing as between the lowest ground and that which is about six miles higher; there is not the faintest sign of diffusion of light on the line between day and night; the effect is that which would take place in what we term a vacuum, but not in the most attenuated part of the atmosphere that lies about our earth. Moreover, the course of the light of a star which goes behind the moon's disc shows clearly that at a mile above the lowest part of the lunar surface the air, if such there be, has less than the thousandth part of the density of that belonging to the earth at the same height. So, if there be any atmosphere at all on the moon, it is in volume, at least, quite unlike that of our planet, and very like the nearest approach to a vacuum which we can in any way produce. There is, indeed, no other valid reason for supposing that any kind of gas or vapor exists about the moon save that it is deemed necessary to have it in order to explain certain changes of color which are deemed to be evidences of organic life. The value of this evidence I shall consider below.

There is reason to believe that the moon has had upon its surface ample material derived from the vulcanoids out of which to form an atmosphere. Regarding the lunar sphere as the offspring of the terrestrial, we may fairly suppose that it received its share of the lighter elements of the original common mass when the separation took place. If we regard the atmosphere of a celestial body as the gaseous remnant remaining on its surface after the more readily solidified elements have consolidated, then the moon should have had an original covering of this kind on a scale proportionate to its total mass, *i. e.*, it should have had an atmosphere equivalent in weight to some inches of mercury. Throughout its recorded history there has evidently been a great efflux of vaporous or gaseous materials from below the crust, in total amount probably enough to have provided an envelope in quantity as great as now lies upon the surface of this planet, yet no trace of it remains. We cannot believe that the materials which should have formed as air on the moon have been largely taken into the crust by chemical action, as is the case on this planet, for there are good reasons to suppose that there is no such action going on there, nor can we accept the suggestion that the air-making gases have been frozen, for while the temperature is at times very low it is for a part of each month probably high enough to permit all the elements which form our atmosphere to return to the vaporous or gaseous state. What, then, is the condition which makes the moon an airless realm?

It appears to me that there is a possible explanation of the lack of an atmosphere on the moon, one that has not been subjected to the inquiry which it deserves; this is, in brief, that the kinetic movement of gases causes their atoms to fly away from the surface into space as rapidly as they are parted from the solid sphere. I understand that this hypothesis has been adduced to account for the separation of certain gases from our atmosphere which are held in that of the sun; an extension of the same view may serve to explain the failure of the moon to retain the gaseous materials which have evidently come to its surface but which the gravitative attraction has not been sufficient to retain against the diffusive effect of the kinetic movement.

THE EXISTING CONDITION OF THE MOON.

The idea that the moon should be the seat of some activities such as operate on the earth is most natural. Again and again observers with much imagination and with poor telescopes have seen what they took to be evidence of volcanic action or of organic life on the surface. With the advance of selenography, these views as to changes on the moon have been by better observations limited to two groups of events. First, changes of form of certain craters, either those of a cataclysmic and permanent nature, such as that which appears to have occurred in the shape of the vulcanoid Linné, and the serial changes in certain other vulcanoids, where the structures return to their original form; second, the lightening or darkening of color of certain patches of the surface as the lunar day advances. There are also some assertions of minor alterations which need to be separately considered.

Of all the observations which point to the conclusion that changes are still going on upon the moon, those which relate to the supposed sudden alteration of Linné are the most important. This vulcanoid lies in the Mare Serenitatis, and was mapped and described by several observers as having a crater about six miles wide and with distinct steep walls. In 1866 it was believed that the structure did not answer to the descriptions for in place of a crater there was found to be a white spot of nearly twice its recorded diameter, and in the center of this field a minute craterlet. Subsequent observations, however, have thrown doubt on this conclusion, and led some selenologists to the opinion that Linné is a structure that varies much under diversities of illumination, and that its variations of aspect, combined, perhaps, with some original bad mapping and servile copying, may account for the seeming change. Other instances, which appear to indicate the sudden appearance of craterlets where none were observed by skilled selenographers, are easily accounted for by the same difficulties arising from the conditions under which we behold the lunar surface. Thus it has been claimed that the lava flow of the vulcanoid Mersenius, which on close scrutiny is seen not to be flat or slightly concave, as is usual in such structures, but quite convex, indicates a change, for it must have been originally level as Schröter, as well as Baer and Mädler, so represents it. A study of this feature will convince any competent observer of the moon, who has had experience with his own work and that of his fellows, that the peculiarity might easily have been overlooked. So, too, with the craterlets on the southwest side of Copernicus, which have not found a place on Baer and Mädler's map, and the continuation of the same craters and a honeycombed appearance of the ground towards Eratosthenes, which Schröter failed to notice. An inspection of the field with a better instrument than those used by the above-mentioned selenographers will show that they may well have searched it a score of times without having a chance to note these rarely visible features. On the whole, the evidence for and against the sudden appearance and disappearance of craters and craterlets, or of features in their structures considered without reference to the probabilities of such changes based on the moon's history, leaves us in a state of doubt as to the occurrence of such accidents. I am inclined to think that the case of Linné is the strongest and that the walls of that vulcanoid may have, in part at least, fallen into the original cavity so as to leave only a small pit in its crater unfilled.

If it be the case that the originally great ramparts of Linné have disappeared, the event may be explained without having recourse to the theory of volcanic action. Against the hypothesis of such action may be set the fact that, though the moon is the subject of constant scrutiny, no trace of such explosive process has been noted. Moreover, if there was volcanic action in the case of Linné, it apparently must have consisted in an outpouring of very fluid lava, which formed the extensive white patch that took the place of the previously existing rampart and pit. In a word, the great wall must have been melted down into the flood. When we consider the fact that none of the other vulcanoids shows a trace of any such flows, that the evidence points to the conclusion that the lavas coming from the interior of the sphere never freely stream forth but consolidate on slopes of high declivity, we see how exceptional, and therefore improbable, is the occurrence of any such event. To the geologist it is inconceivable that in the late stage of the moon's history such an effusion of extremely fluid rock could have taken place. The explanation he would give may be set forth as follows :

Assuming that the lunar crust as the seat of high and varied tensions of contraction and expansion brought about its night and day, and that it abounds in cavities due to the ejection of the large amount of material contained in the ramparts of the vulcanoids, it is conceivable that from time to time ancient but unstable adjustments may be suddenly disturbed. The state of the lunar surface may in a way be compared with that of a Prince Rupert drop, a globular bit of glass greatly affected by stresses which any shock is likely to set in effective action. Now, if on such a surface a meteorite should fall, say a body of some tons in weight, no larger than many that have come upon the earth, the resulting shock might lead to widespread movements that would cause the walls of a vulcanoid to fall in. It is to be noted that there are many ill-defined pits on the moon which may have had this meteoric history, and also that Linné is situated on a wide mare where such stresses are indicated by the continuous ridges and the rills, and where they would be more likely to accumulate than in the higher-lying, irregular country. So if the supposed destruction of this vulcanoid really occurred, a point which will ever remain doubtful, it may thus be accounted for by other than volcanic action. It needs to be so explained if we are to retain our conception of the moon as a sphere which has lost heat in the ratio that the earth has lost it.

The supposed variations in the shape of the twin craters known as Messier, changes which appear to pass through something like a cycle in the course of a lunar period, may possibly be due to the movement of extended masses of rock under the influence of solar heat. Assuming, as before, that a sheet of rock on one or more sides of the pits had, because of its expansion, developed a horizontal joint a few feet below the surface, this slab-like mass might slide to and fro with the variations of temperature. The expansion of a sheet fifty miles in diameter might amount to several hundred feet, enough to make evident alterations in the shape of the cavity. That some such migrations of rock masses under terrestrial compressive strains are possible is abundantly proved by the studies of geologists. Movements of ten miles or more are well ascertained ; the only question is as to the possibility of a field of rock, such as we are considering, returning, in the process of shrinking, to its original position. On the earth, such a plate of stone would most likely be fractured as it cooled, so it could not return to its first state. On the moon, however, such a mass, because its weight is less than one-sixth what it would be on the earth, would encounter less friction in its movements ; moreover, the grinding action of the adjacent surfaces would tend to form a mass of powdery matter between them which would readily shear so that the frictional resistance would be relatively small. The difficulties of this hypothesis are obviously great, but if it is finally determined that there are recurrent changes in process on the moon, such as appear to some observers to take place in Messier, it seems preferable to that of volcanic action, for it does not do violence to all we know concerning the processes of a cooling sphere.

We turn now to the changes of hue of certain fields of the lunar surface such as have been observed by W. H. Pickering and others. These changes are of two somewhat distinct kinds, those which appear to that observer to show the discharge of fumes from certain small craters, and those which are thought possibly to indicate the temporary development of an extended vegetation which is born in the brief season of a lunar day and dies in its night. As regards the blotches of color which seem to indicate eruptions, I have had no chance to see them, but from the account of the phenomena it appears most likely that they are due to peculiarities of reflection much like those which make the rays glow when the sun attains a high angle. The arguments against the existence of any such clouds of vapor floating above the surface of the moon are very strong ; they seem to me, indeed, to be insuperable. The phenomena of occultation prove, as already noted, that at a mile above the surface there is no trace of an atmosphere,—surely not more than the thousandth part of our own. The law of diffusion of gases makes it impossible that there should be any great increase in the density of such air at its contact with the sphere. How, then, could vapors slowly float away as clouds from a crater? If they came forth they should be swiftly and uniformly diffused in the essential vacuum. Change of hue due to the angle of illumination or fluorescence, or both actions combined, affords a far more satisfactory explanation of the observed facts. This explanation has difficulties, but they are much less serious than those we encounter in a hypothesis of volcanic action still existing and producing clouds.

The observations which indicate that extended fields of the lunar surface darken with its advancing day are extremely interesting for the reason that they show a departure from the general tendency of the surface to become brighter with the higher sun. There is no doubt that these changes are of great importance, but I cannot regard them as suggesting the development of any kind of organic life. This question as to the probability of life on the lunar surface has never been adequately discussed, and as the suggestion is recurrent I purpose to set forth below certain considerations which, in my opinion, make it appear to be most improbable that anything like organic structures can possibly develop there.

It is, in the first place, to be noted that all organic forms, from the lowest to the highest, plant and animal alike, absolutely depend for their existence on the solvent action of water on various substances. The conditions of life are that this water shall be readily obtainable either directly from the fluid in which the creatures dwell, from the rain, or from the moisture of the air. In all cases this water must contain free oxygen and carbonic dioxide, as well as certain minerals in solution. Although it is stated that certain lichens develop in rocks within the antarctic circle, where the temperature has never been observed above the freezing point, it may be safely assumed that these plants have now and then received during their growing period and have retained in their bodies water in the fluid state, otherwise their organic processes could not go on. Wherever on high mountains, say above the level of 20,000 feet, the surface of the rock has been examined, no resident life has been discovered. Thus in an air which is surely many times as dense as any that can exist on the moon, terrestrial life, for all its ample opportunities to become reconciled to such environment, has not succeeded in establishing itself at these great altitudes. The conditions for the formation of organisms suited to the higher peaks of the earth are vastly more favorable than they could have been on the moon, yet the result is that they have failed to develop in such conditions.

Whatever were the circumstances, as yet unknown, which led to the beginning of life on this earth, they were evidently of rare occurrence. The successions of organic forms suggest that they have been derived from few if not from one original form; and, further, that these initial stages have long since been lost. It is unlikely that fresh starts in the origination of the lowliest organisms are now making, for with all the skill of a host of well-trained inquirers we have not been able to initiate an organic form. If the existing living species of this earth were destroyed, we do not know by what process a beginning could again be made. So much, however, is plain: First, that all of the existing organic forms have had the initial stages of their development in aquatic conditions, for there alone can the earlier stages of development be attained. Second, that the aqueous stages of the forms which now inhabit the land must have required a very long period of such life before the creatures were ready to enter on the more difficult conditions of the land. It may safely be presumed that a period of development such as is represented by thousands of species of successive forms was necessary to bring the terrestrial organisms into conditions of structure and function where even as the lowliest plants they were fit for stations in the air. This process of reconciliation with the environment demands, among other things, means whereby the spores may be diffused, and with all plants of rapid growth, such as have to be assumed if they are to give color to the surface of the moon, it requires a soil or air for food supply.

It is a favorite assumption with selenographers who adopt the hypothesis of plant life on the moon—a pure assumption—that there may be a thin atmosphere of carbon dioxide next the surface and that in such an air plants would grow with rapidity. This is a natural view, for it is based on the well-known fact that the carbon of plants is largely obtained by the decomposition of that gas, the carbon being taken into the structure and the oxygen set free. But the experiments made by a committee of the British Association for the Advancement of Science clearly showed that terrestrial plants, even the lowlier cryptogams, were not sensibly helped by an increase in the amount of $C\ O_2$ in the air and that any considerable augmentation of that gas was hurtful to them.

Therefore, in view of these facts: that terrestrial plants, notwithstanding all their ample opportunities for so doing, have never been able to reconcile themselves to the conditions which exist at heights where the density of the air is not more than one-third of what it is at the sea-level; that all organic life necessarily had its beginning in the seas or other masses of water; that the conditions of its origin are so peculiar that we have never been able to reproduce them; and that the development of every organic species known to us requires a considerable supply of water,—it appears most unlikely that the moon is now or has ever been the seat of organic life of the sort that exists on this earth.

It cannot well be denied that there may be on the other celestial spheres than this earth forms of association of matter in which other fluids than water may serve as the menstruum in which vital activities develop, and that the essential results accomplished in the organic forms of our planet may be thus attained. But, so far as we know, organic individuals are limited to very narrow conditions: to those in which water is exposed to temperatures between the freezing point and about sixty degrees Centigrade, and which afford air such as that of the earth in density equivalent to not less than what corresponds to a pressure of one-third that normally existing at sea-level. These conditions clearly do not exist, and, so far as we can determine, have never existed on the lunar surface. It is, in fact, very doubtful if any other body in our solar system with the exception of the planet Mars is now in a viable state, for it is not likely that any but the earth, and possibly the Martial sphere, has the necessary combination of water and solar heat which has long existed on this planet.

The foregoing considerations concerning the possibilities of organic life on the moon show clearly that we must exhaust every valid hypothesis to explain the occurrence of changes on that sphere before we assume that they are due to the development of living forms. I would suggest that the patent facts of color-change shown by the blotches and rays, which gain intensity as the sun goes higher, lead naturally to the supposition that these other conditions of darkening are due to a like though somewhat diverse action. We may fairly suppose that the regions which thus darken are covered with crystals which reflect or refract the sun's light in such a manner that they send us less of it when the sun is about vertical than when it is relatively low. We have command of three certainly warranted agents for explaining changes of color in the moon: that of reflections from crystalline surfaces; that of refraction taking place in the interior of translucent crystals; and that of fluorescence. We have a right to combine these actions as needs be to account for such phenomena of varying color as may be observed, for all of them are well within the limits of what we note on the earth, but we have not a like right to bring in hypotheses of organic life when all we know of its conditions on this planet shows that it cannot exist on the lunar surface.

It is naturally painful to conclude that the moon is and always has been deprived of those features of existence which we deem the nobler; that it has never known the stir of air or water or the higher life of beings who inherit the profit of experience and thereby climb the way that has led upward to man. That these large gifts have been denied to the nearest companion of the earth has its lessons for the naturalist, since it clearly shows how vast are the effects arising from the interrelation of actions. The fate of our satellite was probably in large part determined by the ratio between its gravitative force and the energy of the kinetic movement of the gases such as constitute the atmosphere. If that energy had been sufficient to retain them on the satellite, there is no reason, at least so long as the original rotation on its axis continued, why it should not have had the history of a miniature earth. As it is, from the beginning it appears to have been determined that it should have no share in the solar energy which has given the most of the dynamic and all of the organic activities of the earth, and there is no imaginable accident that can alter its state except some catastrophe which may return the solar system to a nebulous mass. Just as it is, our moon is likely to see the sun's light go out.

SUGGESTIONS CONCERNING THE STUDY OF THE MOON.

From the point of view of the geologist and geographer I venture to make certain suggestions concerning the future work of selenographers. In the first place, it may be said that, while the delineation of lunar features has, within a century, been so greatly advanced that of the visible part of the moon we have within the limits of telescopic vision much better maps than of most parts of the earth, the classification of features and their nomenclature are in a very crude shape. There is no sufficient categorizing of the various features, and the names for them, generally suggested by misconceived analogies with terrestrial objects, are often misleading. They serve, indeed, to perpetuate grave errors as to the real nature of the lunar surface. Many of the most conspicuous topographic features are unnamed, as, for instance, the promontories and capes along the shores of the maria. Much of the nomenclature is so inwoven with our records that it would be inadvisable to disturb it, but many changes and additions could be made which would bring some order out of the confusion. I therefore venture to suggest to selenographers that a committee should in some way be formed to undertake a revision, or at least an extension, of the system of names applied to the topography of the moon.

As to further detailed work on the moon, it appears highly desirable that small selected areas should be jointly studied and depicted by several well-trained selenographers, the task being done in such a manner as will enable us to form a judgment, first as to the effects of the personal equation of individual observers in seeing and depicting lunar features, and second as to the effect of diverse conditions of seeing, including the libration, on the aspects of lunar surface. In this way we may hope to attain something like certainty concerning the occurrence or non-occurrence of changes.

It is also desirable that a close comparison be made between some of the more ancient vulcanoids and those of evidently much newer age, as determined by their relations to one another, and this with a view to ascertaining what are the angles of slope of their respective ramparts and those buttress-like structures which I have assumed to be flows of viscid lava. In this way we may possibly obtain some idea as to the effect of the expansion and contraction due to solar heat, or other forces upon their reliefs.

A closer study as to the presence or absence of ash and other ejections of fragmental materials than I have been able to make is desirable. I have given reasons for believing that no such violent expulsion of broken-up lava, *i. e.*, volcanic breccias or ash, took place in the eruptions of the vulcanoids; but the proof of this rests necessarily on negative evidence which requires much scrutiny. This should be given to those cases where large well-developed craters lie adjacent to older like structures. Where there is a honeycombed structure or old ramparts near such newer craters, the surface should be narrowly scanned to find if the depressions have been filled with débris.

The observation of Trouvelot, that the rills are sometimes continued beyond their open fractures by light streaks, needs to be verified, for proof of such condition would go far to show that some of these bands at least are due to the passage upward of vapors which congealed at their point of escape, and afford a fair presumption that all of them are of this nature. This inquiry should be extended so as to determine if any of the radiating streaks are coincident with distinct rills.

The form of the so-called mountains demands a careful inquiry. It is asserted that in some cases the steeper slopes, in certain groups of these elevations, are all, or prevailingly, in a particular versant; this point should be determined. It appears likely that the mountains in different fields vary in shape in a manner which will permit them to be classified according to areas. All such variations are sure to have meaning. As a part of this work, the cones in the center of vulcanoids such as that in Theophilus should be compared with the peaks in the mountain systems.

I have noted that the older vulcanoids in the central field of the moon's surface appear to have been elongated or "spooned" in a north and south direction, and that this change may be due to the loss of the original rotation of the sphere. This point needs further study. If my observations be verified, and it be found that the newer vulcanoids are not deformed as by a collapse of the equatorial bulge due to the loss of rotation, then the time of the change in relation to the development of the surface features may be determined, and as the loss of rotation would have been very gradual it would be incidentally shown that the period during which vulcanoid processes affected the surface was very extended.

The phenomena of contact of the maria with their shores needs close study. I have briefly stated the facts which lead me to the opinion that the lavas of these fields originally and for a brief time rose much above their present level and have since withdrawn from low areas they at first flooded over. If this be affirmed, then we have evidence that the order of fluidity of the lavas in question was far higher than that of the vulcanoids, where, as we have seen, the material appears to have been at a low average temperature, or at least very viscid, so that it consolidated on very steep slopes as soon as it escaped from the craters. Much depends on the determination of the relative temperature of these groups of lavas, for if those of the maria were decidedly hotter than those of the vulcanoids—hotter, indeed, than any molten material which is known to have come forth from the interior of the moon or the earth,—then the presumption that they were due to in-falling bodies is so far affirmed.

It is most desirable to ascertain the circumstances of contact of the lavas of the several maria which are obviously connected. If they are the result of the impact of one falling body, or of several which fell at about the same time and place, then the various connected areas should be perfectly confluent. If the bodies fell here and there, affording separate centers of melting, then there may be a trace of juncture of the lavas where they joined their floods. My own opinion, based on rather scanty observations, is that the confluence of the apparently connected maria is complete, and that their lavas were generated by one incident; the distinctly separated areas, the Mare Crisium and the Mare Australe as well as the Mare Humboldtianum, if the two last named be, indeed, true maria, having been formed apart from the main field, which includes all the other areas classed in this group.

The naturalist, trained in interpreting terrestrial phenomena, learns the value of series in extending his conceptions. It is important that this method of inquiry should be applied to the features of the moon, so that we may have a foundation for a sound knowledge as to the categories into which its structures fall, and the limits of these groups. Thus with the group of vulcanoids a close study of their features by making extended series of their forms will be likely to bring out relations and diversities not now understood. Besides these notable structures, the mountains, cones, and ragged peaks, the rills and valleys, the light streaks and blotches of color, all bespeak the same treatment. It may, indeed, be applied to many other groups of objects.

It is obviously desirable to gather all the information we can concerning the unseen $\frac{41}{100}$ of the lunar surface. This inquiry I undertook more than thirty years ago, but the task was left incomplete. The method of my inquiry was as follows: on the limb of the moon in the successive extremes of libration so-called *mountains* appear. Several of these ranges have a continuity which is found only with the ramparts of the great vulcanoids. Of these, beginning at the north pole and passing by the west around the limb, I noted the range west of the Mare Crisium, another near Neper, the Leibnitz range near the south pole, the great range beyond the Doerfel Mountains, and a succession of like ridges down to ten degrees north. These and other fainter undelineated features appear to be resolvable into arcs of circular ramparts, such as enclose the larger vulcanoids. Plotting these as circles, the result was to establish, by fair hypothesis, over a considerable part of the unseen realm, the existence of a topography like that we see.

Looking closely at the limb of the full moon, observers with good eyes may agree with me in the opinion that certain faint light rays there discernible, though with difficulty, apparently converge to centers on the farther side of the moon. I brought to book enough of these to establish about half a dozen of these centers on the invisible field. A confirmation of these uncompleted observations would reduce the region of the entirely unknown part of the moon to less than one-fifth of its whole surface. I cannot hope to return to this interesting task of looking around the edge of the moon, but it appears to be the most interesting of the many inquiries that demand good eyes, and opportunities for observation when the rays are most clearly visible.

Owing to the difficulty of interpreting objects seen in very oblique conditions, the fields within five degrees of the limb have been much neglected. Among the problems there found is that concerning the existence of maria on the margin of the observable part of the surface. Except possibly in the case of the Mare Australe, the surface of such areas is not visible. I have never been certain that I saw the characteristic dark plain of that mapped sea. The question is whether it be only a little varied ancient portion of the crust or a true mare. It is also a question whether the tips of high peaks are not to be traced on the other side of the comparative level; if this be the case, then it is, if a mare, one of small area. The so-called Mare Humboldtianum also needs close attention to determine whether it be a mare or, as it seems to me, an ancient vulcanoid of large size with rather low walls. If it should be proved that these so-called maria do not belong in that clearly-defined group of features, there will be some reason, from their distribution, for believing that they are limited to the hither side of the sphere.

There are many other lines of work beside that of simple delineation, to which selenographers have so generally confined themselves, which may well engage the attention of those who desire to advance the theory of our satellite. Some of these have been suggested in this memoir; others will present themselves in the course of further inquiry. In such work it should be borne in mind that, relatively few and simple as are the forces which have acted on the moon, in comparison with those which have shaped the earth, they are, in their effects, very complex. The variety of objects on that surface is very much greater than the existing accounts of them would lead the novice to suppose. It is only as they are compared after the manner of the naturalist that we may hope clearly to read the wonderful record of that marvelous dead sphere.

DESCRIPTION OF PLATES.

The following plates have been selected with reference to the illustration of the questions discussed in this memoir. The choice of illustrations has necessarily been limited to those features of which it has been possible to procure good photographic negatives. On this account many interesting structures are not pictured. As a whole, however, these delineations fairly present the more important aspects of lunar topography as seen with good telescopes.

In accordance with the usage of selenographers these plates are printed in the reversed order in which they appear in a celestial telescope. The top of each is the south, the bottom the north, the right hand the east, and the left the west. This will enable the student to compare them with the maps of the moon. Except when necessary for the immediate purposes of this memoir, the structures depicted in the several plates are left unnamed. On many accounts this omission is to be regretted, but an extended effort to designate by name the craters, mountains, etc., showed that to accomplish this end it would be necessary to have key maps for the greater number of these illustrations. If the student desires to determine the name of any of the more considerable features, he can readily do so by comparing the plate with any of the good maps of the moon. For this purpose the map of Elger is recommended.[1] The photographic atlas of the moon by W. H. Pickering, in the Annals of the Observatory of Harvard College, vol. li., 1903, and the same work in a more popular form entitled "The Moon," by Doubleday, Page, & Co., N. Y., 1903, will be found very useful for reference. Other reference would have been made to them in this work, but they were published after the pages which precede this were put to press.

In the description of each plate, attention is called to the more important features which it depicts and occasionally to the place in the text where the matter is discussed. This arrangement of necessity causes many repetitions. It is hoped that the reader will find that the convenience of the method compensates for this awkward mode of presentation, the aim being to provide in the illustrations a basis for a criticism of the theories of lunar structure as near as possible to that afforded by the use of a telescope.

It is suggested that those who desire to spare their time in obtaining what value this memoir may yield, should first read the text and then compare its statements with the facts presented in the plates; remembering that the matters of detail, such as those concerning the rills, the light streaks, and the other more delicate features, can not yet effectively be rendered by photographs.

[1] See *The Moon*, by Thos. Gwyn Elger. London. Geo. Philip & Son, 1895. The map is to be had separately from the volume.

PLATE I.

GENERAL VIEW OF MOON, AGE 6 DAYS. BY S. W. BURNHAM, LICK OBSERVATORY.

Plates I to VIII (inclusive) show the surface of the moon in progressive stages of illumination. Taken at the Lick Observatory.

In plate I the moon appears nearly half full. The crater of Abulfeda is coming into illumination. The most noteworthy features are the maria, which are evidently darker than the general surface. The lowest of these, the M. Serenitatis, is obscurely circular with rather definite margins. In it, on the west or left-hand side, are some faint folds of its floor. Just outside of this sea, to the west, is a rather large distinct crater (Plinius). Horizontally eastward (to the right) in the midst of the sea is a smaller dark crater (Bessel). The same line continued about as far still eastwardly shows in a faint white spot the position of the crater Linné, which is supposed to have been destroyed in 1866 (see p. 70). The mare on which Plinius stands is the M. Tranquilitatis. Next southwardly beyond Theophilus (Plate XV) is the M. Nectaris. On the southern (upper) margin of this sea is the crater of Fracastorius of which the northern part of the rim has evidently been melted down by the sea. This is perhaps the most conspicuous instance of this nature among the several score that may be noted on the margins of the several maria. The northernmost of the maria in this view near the lunar margin is the tolerably circular M. Crisium. South of it is the irregularly shaped M. Fœcunditatis, without distinct boundaries.

The observer should note the considerable range of brightness in the field, also how the craters and other features become fainter near the brightly illuminated margin.

GENERAL VIEW OF MOON, AGE SIX DAYS. BY S. W. BURNHAM, LICK OBSERVATORY.

PLATE II.

MOON 7 DAYS OLD. BY S. W. BURNHAM, LICK OBSERVATORY.

This plate shows the moon one day older than the preceding view. By comparison with plate III the effect of twenty-four hours' advance in the lunar day may be perceived. On the "terminator" or border of the advancing sunlight, a number of large vulcanoids may be seen in a tolerably linear order. The most important of these, beginning with that nearest the equator and reckoning southwardly, are Ptolomæus, Alphonsus, and Arzachel, then with an interval come Purbach, Regiomontanus, and Walter. Traces of a like alignment are visible in other groups of lesser vulcanoids.

At this stage of the illumination some of the light streaks or rays begin to be visible, and may be faintly traced on the left-hand side of the plate when the sun is highest. So, too, the bright patches whence most of the streaks emanate, are beginning to become lucent.

MOON SEVEN DAYS OLD. BY S. W. BURNHAM, LICK OBSERVATORY.

PLATE III.

AGE OF MOON 8 DAYS, 4 HOURS. SEPTEMBER 22, 1890. LICK OBSERVATORY.

In this plate the most noteworthy features are the maria of the western half of the visible portion of the sphere. The rudely circular form of these fields is well shown, also the fact that none of them extend to the margin or "limb" of the moon. The bright, slightly curved ridge in the lower half of the picture facing the partly illuminated mare, the Mare Imbrium, is the Apennines; the large vulcanoid at its southern end is Eratosthenes. The larger pit in the ocean opposite the center of the range is Archimedes; the two craters next to the north are: the nearer, Autolycus, and the farther and larger, Aristillus. The larger of the two dark pits near the northern end of the Apennines is Eudoxus, the smaller Aristoteles. Southeast from these craters lie the Alps, a group of bright peaks extending in a northeast and southwest direction. A faint dark streak shows the position of the Alpine valley. The flat, irregular area north of the range is the M. Frigoris.

Close inspection of this plate will show that many of the vulcanoids have pits or cones on their floors, and that these are very often in the center of these level spaces.

The radiating bands or streaks are beginning to appear.

In the Mare Imbrium, near the western end of the Alps, next north of Aristillus, is Cassini, of which the encircling cone appears to have been partly melted down by the lava of the mare so that it shows as a faint ridge with a distinct central crater.

AGE OF MOON EIGHT DAYS, FOUR HOURS. SEPTEMBER 22, 1890. LICK OBSERVATORY.

PLATE IV.

MOON'S AGE 8 DAYS, 22 HOURS. LICK OBSERVATORY, 1890.

This plate represents the moon as it appears eighteen hours later than shown in the preceding plate. The pictures were taken at different times of the year, which accounts for the difference in the position of the terminator or illuminated margin. It will be observed that several new features have appeared beyond the southern end of the Apennines. The light bands are more visible and the contrast of hue between the maria and the upland country is less distinct.

MOON'S AGE EIGHT DAYS, TWENTY-TWO HOURS. LICK OBSERVATORY, 1890.

PLATE V.

MOON'S AGE 10 DAYS, 12 HOURS. LICK OBSERVATORY, 1890.

The moon as delineated in this plate is thirty-eight hours older than as shown in the preceding plate. The most noteworthy changes are the great advance in the development of the fields of very bright hue, and in the bands radiating from them. These are most evident in the system of Copernicus. The system of Tycho also begins to be evident. This vulcanoid may be identified as the deep large crater with a central cone near the border of the illuminated area. The general irregularity of these light bands is well shown in those about Copernicus. So, too, the fact that they are projections from an illuminated or lucent field about the vulcanoid.

On the shores of the Oceanus Procellarum, east of Plato, near the margin of the sun-lit area, is the Sinus Iridum. This is probably a large vulcanoid which has had the part of its wall next the mare melted down by the lava of that field. (See p. 17.)

The relative absence of large vulcanoids on the maria is noteworthy. Those which exist lie nearly, if not altogether, on fields of high ground which appear to have risen above the floors of the maria and so escaped melting.

The problematical crater Linné now appears as a small white patch near the middle of the eastern side of the M. Serenitatis. (See p. 70.)

MOON'S AGE TEN DAYS, TWELVE HOURS. LICK OBSERVATORY, 1890.

PLATE VI.

MOON'S AGE 14 DAYS, 1 HOUR. JULY 19, 1891. LICK OBSERVATORY.

In this plate the moon is nearly full, the light being oblique enough to illuminate the crater walls on the eastern margin alone.

The maria are well shown nearly to the eastern margin. Separated by a belt of relatively high ground from the Oceanus Procellarum is the large vulcanoid Grimaldi. It has a small crater on its floor near its northern side. This vulcanoid has a floor nearly as dark as the seas. It will be noted that Plato has also a dark floor. On the margin of the Oceanus Procellarum, southwest of Grimaldi, is a crater Letronne, the wall of which that faces the maria is, as in other instances, ruined apparently by the lava of the sea. Other like examples are shown in this neighborhood. On the shores of the M. Humorum, there are three similar instances of crater-walls broken down on the seaward side.

It should be noted that none of the maria distinctly attain the margin of the moon's surface. On the eastern lands the O. Procellarum comes near to the border of the moon, but high rugged land is visible on the very edge. This is more clearly disclosed at certain stages of libration. On the southwest border some observers think there is a sea crossing the border, but, as will be seen, the level land there has not the characteristic dark hue of the maria.

It will be observed that in this nearly vertical light, except Grimaldi and Plato, the craters on the eastern margin only are distinctly visible. Those exceptions are due to the dark color of their floors. There are two or three craters near the south pole which, because they have rather dark bottoms, are faintly seen.

MOON'S AGE FOURTEEN DAYS, ONE HOUR. JULY 19, 1891. LICK OBSERVATORY.

PLATE VII.

MOON'S AGE 21 DAYS, 5 HOURS. NOVEMBER 3, 1890. LICK OBSERVATORY.

In this plate the moon is entering on the fourth quarter. The rays of the Tycho system have nearly disappeared. The two that are nearly parallel remain illuminated. So, too, the system of Copernicus and that of Kepler to the southeast of it remain in nearly full glow.

The vulcanoids near the south pole are better shown in this picture than in any other of the series. That with several craters on its floor is Playfair. Note the craters on the inner face of its wall. The same features can be observed in other like structures in this neighborhood.

The Alps near Plato are fairly well shown, as are also the Apennines that border the western side of the mare. The ruined craters about the M. Humorum are fairly well shown, but are faint.

The tendency to form a crater or cone in the centers of the larger vulcanoids is fairly well shown in those structures about the south pole.

MOON'S AGE TWENTY-ONE DAYS, FIVE HOURS. NOVEMBER 3, 1890. LICK OBSERVATORY.

PLATE VIII.

MOON'S AGE 23 DAYS, 7 HOURS. JULY 28, 1891. LICK OBSERVATORY.

At this stage of the waning moon the most interesting of its fields are no longer visible. There are few that command attention in this plate. It may be noted that the system of light bands and the central patches whence they proceed, that have their center in Kepler, are still very bright. The dark mare-like floor of Grimaldi is visible near the bright margin of the sphere. The observer may obtain something of the impression, such as is afforded by good seeing with a powerful telescope, that the Oceanus Procellarum is a relatively shallow sea, by the number of fragments of what seems to have been the more ancient surface that protrude through it.

MOON'S AGE TWENTY-THREE DAYS, SEVEN HOURS. JULY 28, 1891. LICK OBSERVATORY.

PLATE IX.

MOON'S AGE 21 DAYS, 16 HOURS. 1895.

In this plate is depicted an area from near the moon's equator to near the south pole. On the eastern margin the sunlight is passing from the surface, the evening light being so oblique that the bottoms of the vulcanoids are more or less in shadow. Here and there, in the advancing night, there are lofty peaks on the margin of crater-rims, which still receive a touch of sun and appear as bright points in a black field. On the western margin the surface is still well illuminated, with the consequent effect that the surface appears to be much smoother than it is. A view taken a few hours later would show about as rude a margin as is here depicted.

Perhaps more effectively than any other this view shows how the general surface of the moon outside of the maria is essentially made up of vulcanoids and ridges, the apparently smooth parts appearing so only because the small irregularities are not visible. In this connection it should be noted that near the dark part the surface is seen to be beset by small shallow craters, the smallest visible being more than a mile in diameter, and probably several hundred feet deep. Such pits, in equal numbers to the unit of surface, exist on the bright part to the left when they are observed by the higher light.

The way in which the smaller craters cut the larger is shown at many points in this field of view. So, too, the relative lack of sharpness of outline of the greater vulcanoids as compared with the lesser objects of this group. The low, narrow ridges which surround the pits are insufficiently shown because the light does not bring them out. They are best observed near the uppermost part of the picture.

The generality of the fact that the larger craters have flat floors and that these floors are prevailingly nearly level is well indicated. So, too, the fact that there is a prevailing tendency of these floors to have either a small crater or a cone in or near the center of each circular field. Four such craters in the central part of the area extending in an obscure line from near the base to near the middle of the picture have cones in their centers. In all, about a dozen of the hundred or so instances in which they would be recognizable have this feature. It will be evident that all the craters in this region have their floors far below the level of the encircling ring, and below the general lunar surface.

In sundry instances two adjacent vulcanoids of moderate size have their neighboring walls broken down so that they exhibit the first stage of " crater valleys " with a general north and south axis. There are in all about ten cases of this kind on this field, but several of them are not well-disclosed by this illumination.

MOON'S AGE TWENTY-ONE DAYS, SIXTEEN HOURS. 1895.

PLATE X.

MARE CRISIUM AND NEIGHBORING PARTS OF THE MOON. LICK OBSERVATORY.
ENLARGED TO TWICE THE SCALE OF PLATES I TO VIII.

This plate shows the region about the M. Crisium, the most circular of the seas. It is not completely illuminated, a portion of the western boundary being beyond the light.

In the M. Crisium the most noteworthy feature is the ruined character of its shores as if by the melting action of the lava of the field. There is an obscure step or bench along the shore of the mare as if the lava had subsided, as in the larger vulcanoids.

Northeast of the M. Crisium is a large crater, Cleomedes, with a small pit on its south wall and two craters and a cone on its floor; next farther to the northeast a vulcanoid known as Burkhardt. Note that this has two deformed craters beside it, one to the northwest, the other to the southeast. These features seem to have been produced by some compressive action due to the formation of Burkhardt. East and southeast of this point there is a remarkable confusion of deformed vulcanoids. Near the middle of the M. Fœcunditatis lie two small craters known as Messier, whence extend to the southeast two nearly parallel bands of light. The pits of this pair of vulcanoids have been thought to change their shape in a lunar period. By some early observers the bands were supposed to be artificial objects, and one astronomer suggested that they were built by the selenites to signal the people of the earth. There are several ridges on the mare to the westward of Messier.

The large vulcanoid to the southwest of Messier with a central crater, just beyond three smaller pits of nearly the same size, is Langrenus, next south Vendelinus, yet farther south Petavius. The first and last of these show distinct benches on their inner walls. The last has many pits on its crest.

On the southern margin of the M. Nectaris is Fracastorius, another vulcanoid with the seaward side of its wall demolished by contact with the maria, though it is still traceable ; there are several other like instances about this mare.

MARE CRISIUM AND NEIGHBORING PARTS OF THE MOON. LICK OBSERVATORY.
ENLARGED TO TWICE THE SCALE OF PLATES I TO VIII.

PLATE XI.

ENLARGED VIEW OF A PART OF THE APENNINES.

This plate shows a portion of the Apennines near the Palus Putredinis, an embayment of the M. Serenitatis where it breaks through the mountain wall and nearly connects with the M. Imbrium. The three large vulcanoids are Archimedes, Autolycus, and Aristillus. The very steep or even undercut character of the front of the Apennines is well-known. So, too, the varied condition of the old craters, breached on the side towards the mare. These features strongly suggest a melting action of the once-fluid lava of the mare.

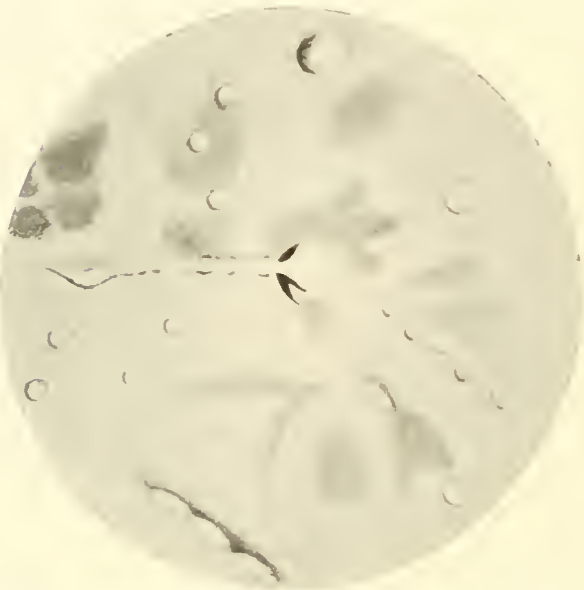
ENLARGED VIEW OF A PART OF THE APENNINES.

PLATE XII.

HYGINUS AND THE NEIGHBORING FIELD.

This plate is intended to show the general character of the area in which lie the Hyginus clefts. It should be noted that parallel and near to those of Hyginus there is another which also intersects a vulcanoid. It is less perfect but evidently of the same nature. A yet more indistinct object of the same nature lies near the west wall of the large crater north of Hyginus.

The group of mountains lying near Hyginus shows the elongate character which those ridges often assume. In other parts of the field they are distinctly conical. Near the clefts is a good example of crater valleys. Others less distinct lie near the southern border. A large vulcanoid near the margin of the plate has evidently had a part of its rim broken down, probably by the lava of the neighboring mare.



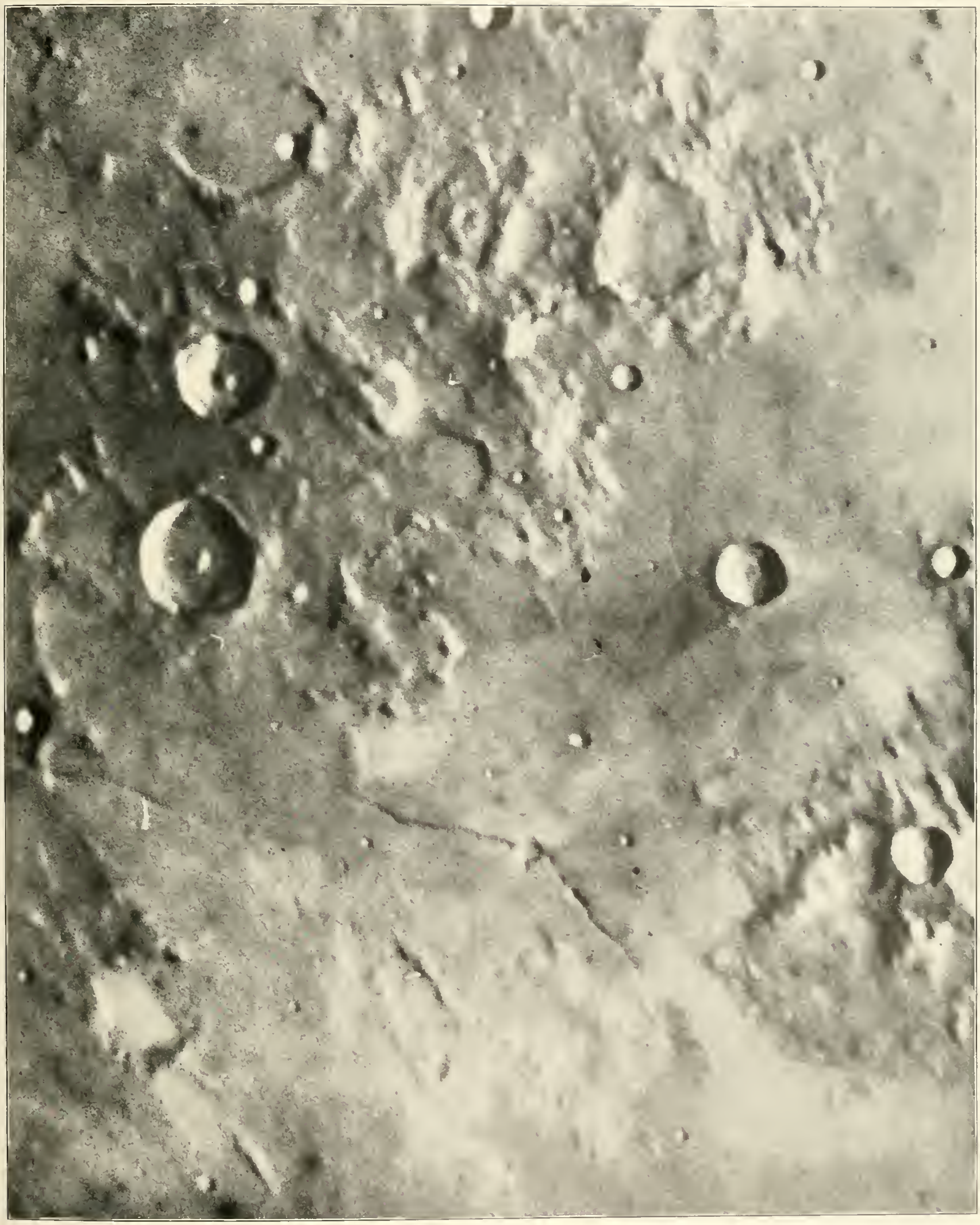
Hyginus from a Drawing with the 13-inch Equatorial at the Allegheny Observatory. F. W. Very, Del., 1890. Three-eighths Size of Original Drawing.

The difference between the features shown in this plate and the drawing figured herewith will serve to show the reader how diverse are appearances of the moon's surface under different conditions of observation.

This drawing may be compared with the photographs of the same object (Pls. XII, XXII) to show the relative minuteness of detail grasped by a photograph and by the eye. It shows the vulcanoid Hyginus with the remarkable clefts which proceed from it as exhibited in a drawing. The crater is in no wise exceptional, except for the fissures which break through its encircling wall and extend for a great distance on either side. These are among the most instructive of this group of lunar features.

It should be noted that the general contour of the walls on either side of the clefts indicates that a number of small craters were first formed and then divided by the formation of the vent and the separation of its walls. That such was the case is well shown by the fact that the cleft on the right has a part of the ring of at least four of these small vulcanoids on one side of its wall and a part on the other. There is a faint trace of the same feature in the rift on the left of Hyginus. A like separation has taken place in the walls of the principal crater. The fact that the floor of this crater is apparently not divided probably indicates that it was molten at the time when the rupture occurred, or that it afterwards was so.[1] The level surface of the bottom of the clefts can best be explained by supposing that they, too, are floored by lava which entered them at some time after they were formed. It is probable that this lava came from the depths, for the reason that, as elsewhere noted, there is reason to believe that the lunar lavas were not sufficiently fluid to flow readily. (See p. 12.) The facts appear to indicate that this crevice was formed before the interior of the moon had ceased to be fluid.

[1] Elger states that he has seen, though faintly, traces of the cleft crossing the floor of the crater. If this observation was well made, then we have to suppose that the lava did not quite fill this part of the rift, which does not appear on this drawing, though it exhibits features that Elger had evidently not observed. Such developments are very common in sketches of lunar structures.



HYGINUS AND THE NEIGHBORING FIELD.

PLATE XIII.

PHOTOGRAPHED BY RITCHEY WITH 40-INCH TELESCOPE, USING YELLOW COLOR SCREEN AND ISOCHROMATIC PLATE.

This plate shows more than half of the fourth quadrant or the southwest quarter of the moon's visible surface, taken at about three-fourths full. The area extends from the equator on the lunar margin to about 55 south latitude, and from near the polar axis westwardly two-thirds the distance to the margin of the visible field—a district rich in instructive objects.

On the lower part of the plate is a portion of the Mare Tranquilitatis ; on the middle of the left-hand side a portion of the Mare Nectaris. The observer should note the features of contact of these maria with the higher ground against which they lie, especially that there are some indications of a gradual passage from the rough surface of the upland to the relatively smooth floors of the maria, and also that several of the rings (at least five) facing the M. Tranquilitatis have the side towards that area destroyed. The wrinkles on the floor of this sea are fair but not good examples of the mountain-like ridges that are found on those areas. That on the margin of the M. Nectaris, extending northward from a crater half in the shadow, is noteworthy.

About a score of the vulcanoids in this field show the tendency to "spooning" or elongation of the crater in a general north and south direction, in some instances rather northeast and southwest. In the northeast part of the field some of them pass into crater valleys with a distinct northeast and southwest axis. In a few instances the axes of these deformed craters are inclined to the southeast and northwest. So that there appear to have been three different lines of strain developed on this part of the lunar crust.

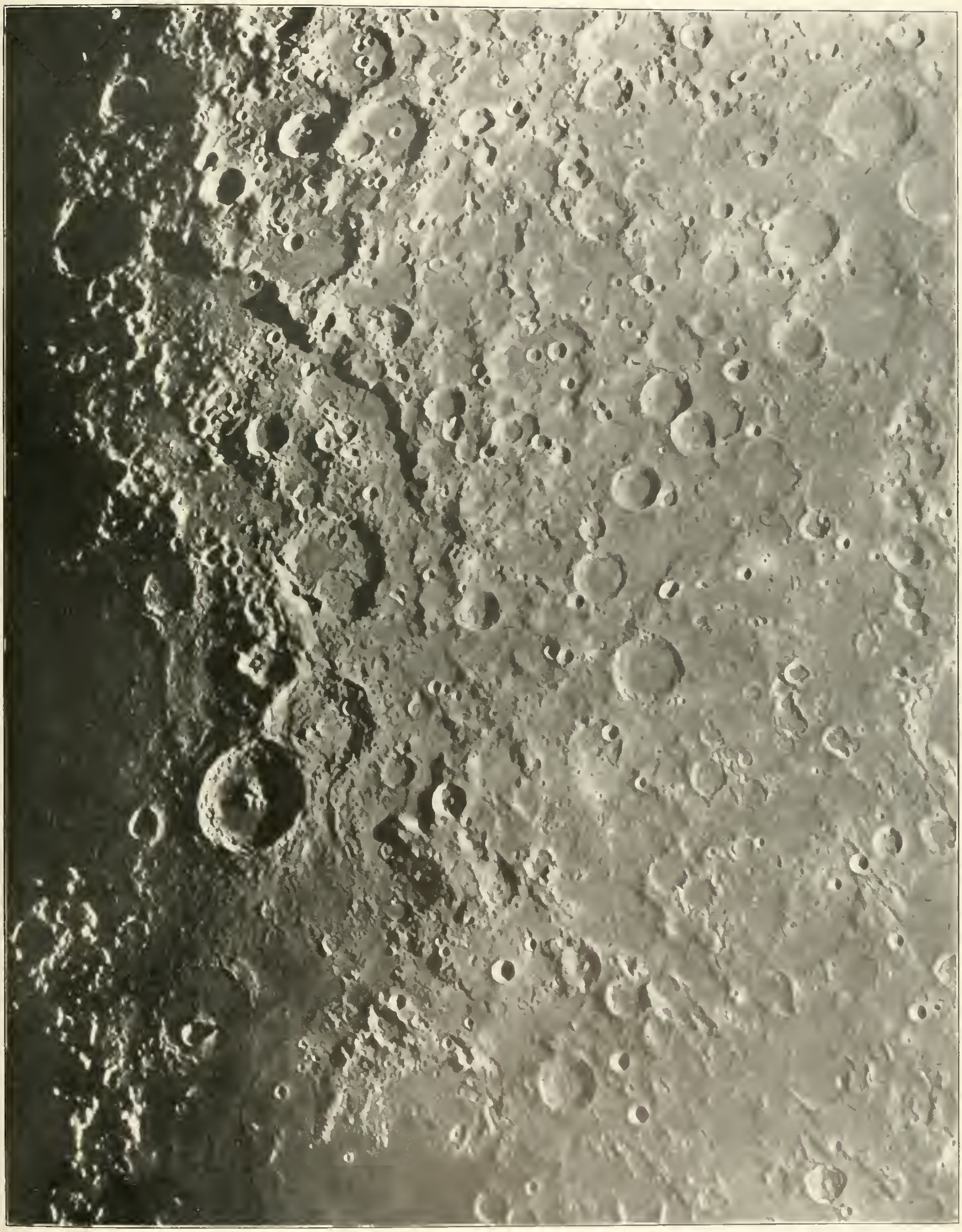
The large, deep vulcanoid with the steep, ragged peaks rising from its floor, near the dark margin on the left, and about one-third the distance from the bottom of the plate, is Theophilus, one of the noblest structures on the moon. The width of the crater is about sixty-four miles ; the greatest height from the floor to the crest of the wall eighteen thousand feet. The central mass, composed of several sharp peaks, rises about six thousand feet above the lava plain. In the center of these masses there appears to be an obscure crater about half a mile in diameter. The terraces in the inner wall of the cone are indistinctly shown.

It is to be noted that Theophilus in its development has partly invaded Cyrillus, the next large vulcanoid on the southeast, and also that the older structure seems more ancient with less steep slopes and exhibits a generally ruined appearance. Cyrillus is also more "spooned" or drawn out in a north and west direction than Theophilus. South of Cyrillus, at a distance of half its width, is Catherina. This crater is met by another of half its diameter which has developed on one side of its floor. From near the southeastern margin of Catherina a beautiful row of small craters extends eastwardly for a distance of over two hundred miles to the large vulcanoid Abulfeda. This is perhaps the most noteworthy crater row on the moon.

The long curved wall extending from Piccolomini, near the upper left hand corner (the large crater with its floor in shadow), to the east side of Catherina is the Altai Mountains. It should be noted that this step-like structure obscurely extends northwards to the M. Tranquilitatis, where it forms an irregular ridge-like promontory.

It should be observed that about a dozen of the larger vulcanoids have either a crater or a cone in the central part of their flat bottoms. In some instances on the brightly illuminated parts those structures exist, but are not revealed by the illumination.

The larger details of the general surface of the moon on the area to the left of the Altai escarpment are perhaps better shown here than in any other plate. They are rarely so well revealed in even the best telescopes. In the best seeing the trained eye has a chance to observe perhaps one-half more than is here shown. Note near the margin southwest of Catherina the existence of obscure ancient craters, their walls broken and shoved about, as well as the mingling of small cones and craters, suggesting that craters began with dome-like cones (see p. 30).



PHOTOGRAPHED BY RITCHEY WITH FORTY-INCH TELESCOPE, USING YELLOW COLOR SCREEN AND ISOCHROMATIC PLATE.

PLATE XIV.

PART OF THE SHORE OF THE OCEANUS IMBRIUM. BY M. HENRY, PARIS OBSERVATORY.
AGE OF MOON, 240 HOURS.

In this plate there are a number of features discernible in the others, but here better exhibited than elsewhere in this series of illustrations. The Oceanus (or mare) Imbrium occupies the central part of the picture, its northern, western, and a part of its southern margin being shown. The large vulcanoid with the dark floor on the northern coast is Plato. South of it, a little way out upon the mare, is a group of noble peaks called the Teneriffe Mountains. The loftiest rises about eight thousand feet above the mare.

Following around the shores of the Oceanus Imbrium to the left hand, we note near Plato the great group of the Alps where there are some hundred peaks, one rising twelve thousand feet above the mare. Cutting across them the Alpine valley is faintly shown. Farther to the left we find the Caucasus, a ridge-shaped mountainous district, with one of its many peaks nineteen thousand feet high. South of this (upwards on the plate) is the passage connecting the Oceanus Imbrium with the Mare Serenitatis. On the left hand from this strait the first white spot is Linné (see p. 70). On the right of the strait are two craters, the lower Aristillus, the upper Autolycus. Farther up to the right is Archimedes. It is about fifty miles in diameter. Above the last-named structure is an unnamed mountainous district. The lower parts of these fields appear to have been swept over by the lava of the mare, but the higher are unaffected by it. The shore to the left of this field from the strait southward is termed the Apennines. The fine crater near the end of their distinct line is Eratosthenes. Farther on, out in the dark field of the Oceanus Procellarum, is the great vulcanoid Copernicus. Just below it, faintly shown, is a group of elevations termed the Carpathian Mountains.

PART OF THE SHORE OF THE OCEANUS IMBRIUM. BY M. HENRY, PARIS OBSERVATORY.
AGE OF MOON, 240 HOURS.

PLATE XV.

CENTRAL PORTION OF THE MOON FROM THE M. SERENITATIS TO STÖFLER.

BY M. HENRY, PARIS OBSERVATORY.

All the more important structures shown in this plate have been displayed in the preceding plates under different conditions of illumination. The most noteworthy features here illustrated are the seas. The lowest or northernmost is the southern part of the M. Serenitatis, which will be seen to have its surface apparently somewhat lower than the adjacent M. Tranquilitatis. This latter passes on the left hand or western side into the M. Fœcunditatis, which is shown only in small part, and on the south into the M. Nectaris. At the southern end of the M. Nectaris is the great vulcanoid Fracastorius with its northern wall broken down apparently by the melting action of the lava of the mare.

South of the distinct crater of Menelaus, a little to the right of the uppermost part of M. Serenitatis, at about one-fifth the distance from the bottom of the plate towards the top, is a very irregular vulcanoid, Julius Cæsar, which is partly broken down by the neighboring mare. Touching the northern or lower margin of Julius Cæsar is a good example of a crater valley. Several others are included in this plate. About half the width of Julius Cæsar farther to the south is the Ariadæus cleft, one of the straightest fissures on the moon.

On the most illuminated part of this plate the bright streaks begin to be traceable ; they are most visible on the M. Nectaris.

CENTRAL PORTION OF THE MOON FROM THE M. SERENITATIS TO STÖFLER.
BY M. HENRY, PARIS OBSERVATORY.

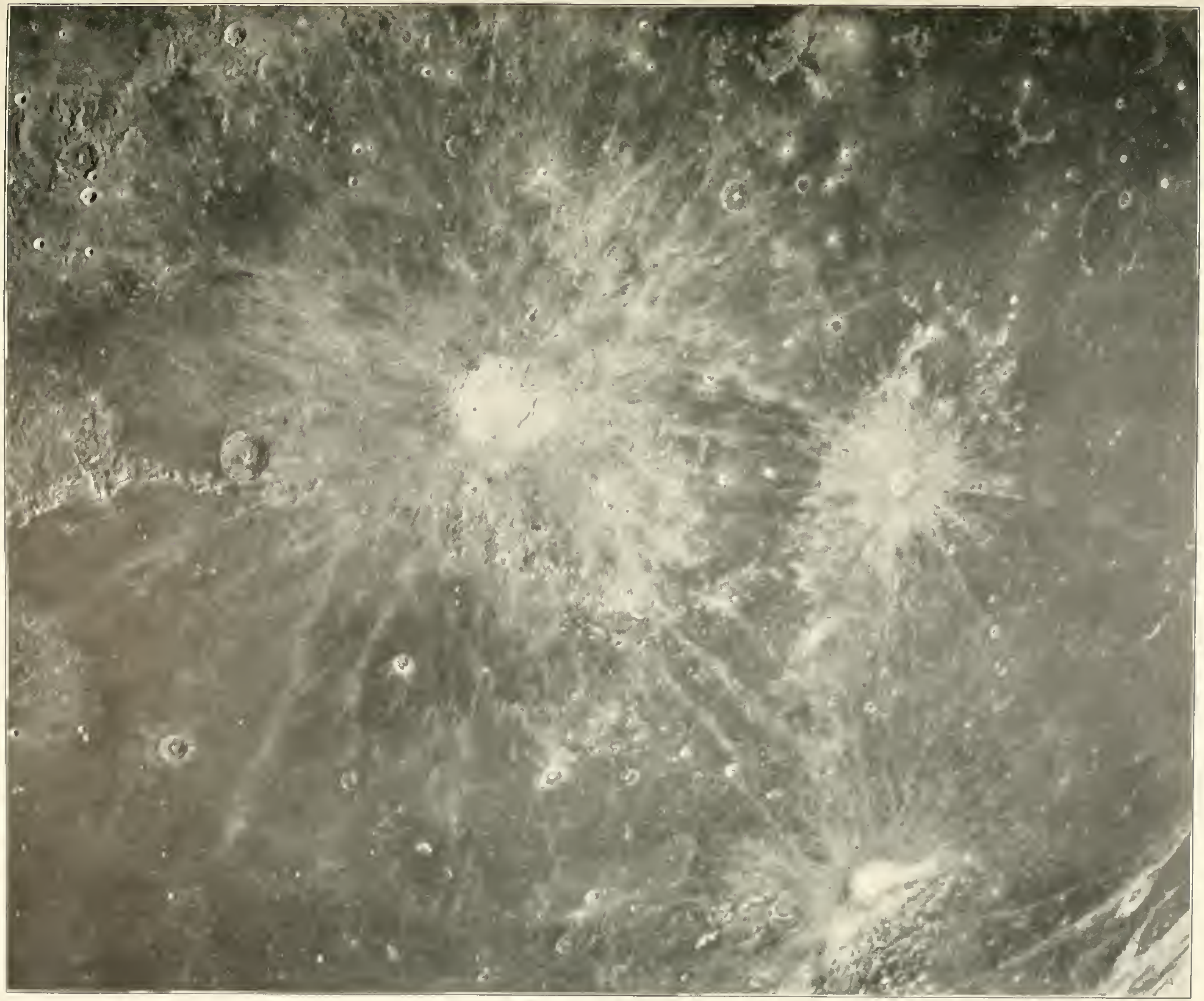
PLATE XVI.

COPERNICUS AND KEPLER. PHOTOGRAPHED BY RITCHEY. SCALE, ONE-HALF METER TO MOON'S DIAMETER.

The following ten plates were photographed by G. W. Ritchey with the forty-inch Yerkes refractor, with color screen and isochromatic plate. As will be noted, they in part repeat the features exhibited by the other plates of this series, yet in all instances they serve to supplement or extend the information afforded by them.

The most important features exhibited by plate XVI are the systems of bright rays of Copernicus, Kepler, and Aristarchus. These three ray systems, though less extensive than those of Tycho, taken together constitute the greatest exhibition of the bright bands that exist over the northern part of the surface. The complex branched nature of these bands is particularly well shown, better, indeed, than the writer has ever been able to note with the telescope. The fact that the bright bands of each system are prolongations of a central bright field is tolerably well shown.

Although owing to the high sun and the consequent absence of shadows, Copernicus in this view hardly appears as an elevation, it is, under favorable conditions of illumination, perhaps the noblest object on the moon. The wall on the eastern side, according to the estimates of Schmidt, rises to a height of twelve thousand feet above the adjacent plain. The outer slopes of the cone are strongly ridged as by the flow from the crater of lavas which cooled on the steep slopes; some of these are faintly traceable in the plate.



COPERNICUS AND KEPLER. PHOTOGRAPHED BY RITCHEY. SCALE, ONE-HALF METER TO MOON'S DIAMETER.

PLATE XVII.

CRATER REGION ABOUT THEOPHILUS. PHOTOGRAPHED BY RITCHEY.
SCALE, THREE-FOURTHS METER TO MOON'S DIAMETER.

A portion of this field, including the crater Theophilus, is shown in other plates. This most important structure lies just below the middle of the plate near the margin of the illumination.

The details of structure of the lunar surface, as shown on the margin of the illuminated field, are better exhibited in this picture than in any other; perhaps better than in any other photograph that has been published. The more important of them have been noted in the descriptions of preceding plates, but attention may well be called to certain of these features, viz., to the numerous shallow craterlets near Theophilus, to sundry wrecked craters in the same field, and to the association of small cones and small craters in the region south (upward on the plate) from Theophilus.

The frequent deformation of craters by elongation is fairly well indicated by several vulcanoids within the field of view. The invasion of the material of the maria is well shown in the region about Theophilus, and, as before noted, the central peak on the crater floor of that structure with its fairly distinct central pit is admirably depicted.

It is well to note the passage from the very distinct exhibition of the structures on the terminator, the margin of the illuminated field, to the obscurity of similar features when the sun is more than forty-five degrees above the horizon.

CRATER REGION ABOUT THEOPHILUS. PHOTOGRAPHED BY RITCHEY.
SCALE, THREE-FOURTHS METER TO MOON'S DIAMETER.

PLATE XVIII.

MARE SERENITATIS. PHOTOGRAPHED BY RITCHEY. SCALE, THREE-FOURTHS METER TO MOON'S DIAMETER.

This plate shows the whole of the Mare Serenitatis ; on the upper right-hand corner a part of the M. Vaporum ; on the lower corner of the same side portions of the Mare (or oceanus) Imbrium, known as the Palus Nebularis. The largest vulcanoid near the dark margin is Posidonius. The bright patch showing no distinct structure, which lies on the parallel of Posidonius, about two-thirds across the field, is the problematical Linné. The partly illuminated portion of the mare below Posidonius is the Lacus Somniorum.

The most noteworthy structures exhibited in this plate are as follows : The great mountainous ridge which traverses the mare in a general north and south direction (this structure more distinctly resembles a terrestrial mountain-chain than any other elevation on the moon); the field abounding in conical elevations in the lower part of the plate ; the crater of Le Monnier just above Posidonius, which has a part of its wall apparently broken down by the mare, and the crater valleys near the upper right-hand corner of the plate. There are a number of clefts, commonly known as rills, which are fairly well shown. A group of these lies just below Plinius, the large crater with a bright central cone emerging from the shadow of the crater wall, situated near the upper margin of the plate. Another notable group is found in the left-hand lower section of the plate. Faint traces of craters may be seen in these clefts.

It may be noted that a number of the larger vulcanoids here depicted exhibit that tendency to a development in a meridional direction which has been termed in this text "spooning." In Posidonius and the smaller vulcanoid, Jansen, on the margin above it, the southern (upper) walls are thus indented.

MARE SERENITATIS. PHOTOGRAPHED BY RITCHEY. SCALE, THREE-FOURTHS METER TO MOON'S DIAMETER.

PLATE XIX.

RAY SYSTEM ABOUT TYCHO. PHOTOGRAPHED BY RITCHEY. SCALE, THREE-EIGHTHS METER TO MOON'S DIAMETER.

This, the most extensive of the ray systems of the moon, has its origin in the field about Tycho, the large vulcanoid to which the numerous bands apparently converge. It appears under the high sun as a large pit with a compound central cone. The rays of this system should be compared with those which have their centers in Copernicus and Kepler. In these last named groups the streaks are developed on relatively level ground, while on that of Tycho they intersect a rugged surface.

On the right hand, some of the bands may be seen crossing the Mare Nubium. Two of them of great length are seen to be nearly parallel for a distance of some hundred miles.

A number of large vulcanoids, partly in shadow, are shown on the southeast margin of the moon. Of these the largest is Schiller. Its length, which is one hundred and twelve miles, will serve as a scale in estimating that of the rays.

RAY SYSTEM ABOUT TYCHO. PHOTOGRAPHED BY RITCHEY. SCALE, THREE-EIGHTHS METER TO MOON'S DIAMETER.

PLATE XX.

COPERNICUS AND SURROUNDINGS. PHOTOGRAPHED BY RITCHEY, NOVEMBER 21, 1901, 7 HOURS 32 MINUTES P.M., CENTRAL STANDARD TIME. EXPOSURE, ONE SECOND. SCALE, THREE-FOURTHS METER TO MOON'S DIAMETER.

This plate of Copernicus should be compared with the plates showing the same structure under more nearly vertical illumination when the light bands appear.

In the plate the lower level area is a part of the Mare Imbrium. This is bordered on the left by a portion of the high country known as the Apennines, which extend as far towards the center of the plate as the large crater Eratosthenes. To the left, separated by a little more than the width of Copernicus, is the faintly outlined vulcanoid known as Stadius, which appears to have been in large part melted down by the lava of the Oceanus Procellarum which has invaded this field. On the right hand from Eratosthenes, the margin of the mare is formed by the peaks of the Carpathian Mountains. Immediately above Copernicus is a small, double crater, one of the simpler crater valleys.

The area about Copernicus exhibits several very interesting types of structure. The Carpathian Mountains show the mare penetrating into several rude craters, the seaward faces of which have had their walls destroyed by the fluid lava. A broken line of small craters lies midway between Copernicus and Eratosthenes. At either end it verges into a narrow crater valley of the "rill" type. The central part of the upper half of the field abounds in very perfect cones which are associated with small crater pits.

COPERNICUS AND SURROUNDINGS. PHOTOGRAPHED BY RITCHEY, NOVEMBER 21, 1901, SEVEN HOURS THIRTY-TWO MINUTES P. M., CENTRAL STANDARD TIME. EXPOSURE, ONE SECOND. SCALE, THREE-FOURTHS METER TO MOON'S DIAMETER.

PLATE XXI.

MARE NUBIUM AND SURROUNDINGS. PHOTOGRAPHED BY RITCHEY, NOVEMBER 21, 1901, 7 HOURS 32 MINUTES P.M. EXPOSURE, ONE SECOND. SCALE, ONE-HALF METER TO MOON'S DIAMETER.

In this plate Copernicus is the large vulcanoid on the lower margin. The large crater near the upper margin, a little to the right of the center, with a cone somewhat to the right of its center and "rill" on its floor, is Pitatus. The three great vulcanoids in a row extending in a north and south direction, are, in succession from the lowest towards the upper margin of the plate, Ptolemæus, Alphonsus, and Arzachel. The large deep crater below and to the right of Pitatus, with a divided central cone, is Bullialdus.

The most noteworthy features in this plate are found in the many instances in which the lavas of the maria have partly destroyed the vulcanoids within their fields. In the upper right-hand fourth of the plate, there are a dozen or more of these ruined craters, some of them with their walls almost effaced. In this part of the field there are several important rills. Some of these are evidently rows of craterlets in which the adjacent walls of the pits have been broken down so as to form a ragged cleft. A number of these lines of craterlets are traceable on the external slopes of Copernicus. The long, dark line, sixty-five miles in length, in the upper third of the plate, a little to the left of the center, is the Straight Wall, the most extensive fault known on the moon. The height of its cliff is about five hundred feet. The crescent shaped structure at its southern (upper) end is the remnant of a crater, the remainder of the margin having been destroyed by the lava of the mare. To the right of, and near by the Straight Wall, is a rill extending in a slightly curved course for a length of about forty miles, terminating at either end in a distinct craterlet.

The brightly illuminated part of the field depicted on this plate, that to the left of the center, exhibits many excellent examples of crater valleys, which in their series afford something like a passage from the condition of rills to those wider depressions.

MARE NUBIUM AND SURROUNDINGS. PHOTOGRAPHED BY RITCHEY, NOVEMBER 21, 1901, SEVEN HOURS THIRTY-TWO MINUTES P. M. EXPOSURE, ONE SECOND. SCALE, ONE-HALF METER TO MOON'S DIAMETER.

PLATE XXII.

MARE TRANQUILITATIS AND SURROUNDINGS. PHOTOGRAPHED BY RITCHEY, AUGUST 3, 1901, 2 HOURS 30 MINUTES A.M., CENTRAL STANDARD TIME. EXPOSURE, $\frac{3}{4}$ SECOND. SCALE, THREE-FOURTHS METER TO MOON'S DIAMETER.

This plate includes nearly the whole of the Mare Tranquilitatis and, on the lower margin, a portion of the M. Serenitatis. The large crater near the strait connecting these maria is Plinius. The highland nearest to it is the promontory of Acherusia. On the southern, or upper, margin the view extends to the flanks of Theophilus.

The most noteworthy features in this plate are the mountain ridges on the maria, the manner in which the maria come in contact with the higher ground, the numerous crater valleys, and the great "rills."

It may be noted that ridges on the maria exhibit little trace of corresponding troughs between them, such as are usually found in terrestrial mountain chains.

The contact of the maria with the high ground has evidently resulted in the partial melting of the walls of several vulcanoids. Where these structures are not thus affected they are, apparently, in origin later than the formation of the maria. The crater valleys are abundant on the right-hand or eastern side of the field. Some of them have been invaded by the lava of the mare.

Some of the greater rills are very well shown. That on the extreme right side is Hyginus (see p. 44). It will be observed that the course of these rills is at high angles to the prevailing direction of the ridges on the mare.

MARE TRANQUILITATIS AND SURROUNDINGS. PHOTOGRAPHED BY RITCHEY, AUGUST 3, 1901, TWO HOURS THIRTY MINUTES A. M., CENTRAL STANDARD TIME. EXPOSURE, THREE-FOURTHS SECOND. SCALE, THREE-FOURTHS METER TO MOON'S DIAMETER.

PLATE XXIII.

MARE IMBRIUM AND SURROUNDINGS. PHOTOGRAPHED BY RITCHEY, NOVEMBER 21, 1901, 7 HOURS 32 MINUTES P.M., CENTRAL STANDARD TIME. EXPOSURE, ONE SECOND. SCALE ONE-HALF METER TO MOON'S DIAMETER.

This plate depicts the western two-thirds of the Mare Imbrium : it does not show the interesting Sinus Iridum on its northern shore, nor the Harbinger Mountains on its eastern side. The most noteworthy features are the relatively level surface of the mare and the greater vulcanoids and peaks on its margin, or in its midst, and the Alpine valley on its northwest side.

The great crater near the lower margin of the mare is Plato. This crater has a diameter of sixty miles, and is very nearly circular. It is separated from the M. Imbrium by little more than its own wall, and from the narrow M. Frigoris on the north by a field of upland that declines gently to that mare. This field is thickly beset by small cones. The interior walls of the crater of Plato rise in general to a height of about four thousand feet above its floor. At some points, however, this wall is over seven thousand feet in height. The floor of the crater appears in the plate to be smooth and of a rather even, very dark hue. It is, however, the seat of rather extensive topographical and color features. There are at least six crater cones, about forty patches of peculiar coloration. The failure of these markings and structures to appear on this admirable plate may be taken as a measure of the difference between what is shown by the best reproductions of photographs now obtainable and the revelations of the telescope under the most favorable conditions.

On the sea south of Plato is a group of remarkable peaks. Those on the extreme right are known as the Straight Range ; those on the center as the Teneriffe Mountains ; the solitary peak yet farther to the west is Pico.

The wide cleft to the left of Plato, about one hundred miles away, is the Alpine valley. Owing to the high sun it is not well shown.

The three great vulcanoids near the left-hand margin of the mare are : the largest Archimedes, the intermediate Aristillus, and the smallest Autolycus.

MARE IMBRIUM AND SURROUNDINGS. PHOTOGRAPHED BY RITCHEY, NOVEMBER 21, 1901, SEVEN HOURS THIRTY-TWO MINUTES P. M., CENTRAL STANDARD TIME. EXPOSURE, ONE SECOND. SCALE, ONE-HALF METER TO MOON'S DIAMETER.

PLATE XXIV.

ARISTOTELES, EUDOXUS, AND SURROUNDINGS. PHOTOGRAPHED BY RITCHEY, OCTOBER 13, 1900, 2 HOURS 40 MINUTES A.M. EXPOSURE $\frac{1}{2}$ SECOND. SCALE, THREE-FOURTHS METER TO MOON'S DIAMETER.

In this plate the large vulcanoid near the top of the lower third of the field, that which cuts the ring of the smaller crater on the left of its wall, is Aristoteles; the somewhat smaller structure just above is Eudoxus; that near the upper left-hand corner is Posidonius. On the right hand, at the same level as Aristoteles, the great Alpine valley is partly seen, the illumination being too nearly vertical to show it well.

Among the noteworthy features exhibited by this plate the following are the most important:

The wall of Aristoteles evidently has broken that of the small unnamed crater adjacent to it on the west (left-hand) side. This shows that Aristoteles was in activity since the smaller vulcanoid was formed. The inner slopes of the first-named crater abound in rude terraces. Its limited floor bears numerous cones.

South of Eudoxus is an extensive field of elevations known as the Caucasus Mountains. The western portion of this field peculiarly abounds in cones and craterlets of about the same diameter as these cones, suggesting that the two groups of structure are in origin in some way related. Certain other good examples of these cones are exhibited in the lower part of the plate.

To the west of Eudoxus is a great, irregular vulcanoid with a large crater (Burg) somewhat excentrically placed on its floor. On this floor are some remarkable rills.

The greater part of the upper third of the plate is occupied by the Mare Serenitatis. A portion of its mountain-like ridges is well shown.

ARISTOTELES, EUDOXUS, AND SURROUNDINGS. PHOTOGRAPHED BY RITCHEY, OCTOBER 13, 1900, TWO HOURS FORTY MINUTES A. M. EXPOSURE, ONE-HALF SECOND. SCALE, THREE-FOURTHS METER TO MOON'S DIAMETER.

PLATE XXV.

CLAVIUS, LONGOMONTANUS, TYCHO, ETC. PHOTOGRAPHED BY RITCHEY, NOVEMBER 21, 1901, 7 HOURS 32 MINUTES P.M., CENTRAL STANDARD TIME. SCALE, THREE-FOURTHS METER TO MOON'S DIAMETER.

In this plate the large crater, only partly illuminated, on the line of the terminator and cut by the upper edge of the plate, is Klaproth. Just below Klaproth is Blanchianus, which on its lower margin nearly touches the wall of Clavius, the largest structure in the field. Clavius is one hundred and forty-two miles in diameter. North of Clavius, on the edge of the illumination, is Longomontanus. Nearly in the center of the plate is Tycho, about which the great ray system, visible under a very high sun, originates. This structure may be recognized by its central, sharp, irregular cone. The large vulcanoid near the center of the lower part of the plate is Pitatus, situated on the margin of the Mare Imbrium. It may be better identified by the "rill" on the northeast part of its crater floor.

The most noteworthy features of this plate are as follows: The abundance of relatively large vulcanoids; the difference in the nature of their floors, some being relatively smooth, others much varied by pits and craters, and the association of small cones and craterlets of like horizontal section, in all parts of the field where the light is favorable for their exhibition.

The effect of the lava of the mare, when it comes in contact with the high ground, also deserves attention. It appears to have more or less completely destroyed the walls of several vulcanoids with which it came in contact.

CLAVIUS, LONGOMONTANUS, TYCHO, ETC. PHOTOGRAPHED BY RITCHEY, NOVEMBER 21, 1901, SEVEN HOURS, THIRTY-TWO MINUTES P. M., CENTRAL STANDARD TIME. SCALE, THREE-FOURTHS METER TO MOON'S DIAMETER.

SMITHSONIAN CONTRIBUTIONS TO KNOWLEDGE

PART OF VOLUME XXXIV

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On the Modern Reflecting Telescope and the Making and Testing of Optical Mirrors

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(No. 1459)

CITY OF WASHINGTON
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INTRODUCTION.

For few papers published by the Institution has there been a more constant demand than for the memoir by Professor Henry Draper, entitled "On the Construction of a Silvered Glass Telescope," originally issued forty years ago, in 1864.

The paper is of remarkable merit as a summary of, and an addition to, the knowledge existing at the time, but during the long interval which has elapsed, progress has been made in various directions and by various hands.

On the occasion of a new edition of this classic memoir, it was sought to give an account of the latest knowledge on the subject, and I was gratified to be able to obtain from Mr. Ritchey, whose labors in this direction are so well known, an account of the processes which he has employed for making the great mirrors that have been so effective at the Yerkes Observatory, and it has been decided to republish, with the original Draper memoir, but as an entirely independent contribution to the subject, the present article by Mr. Ritchey.

The great refracting instruments which have been produced in recent years have not superseded the use of the reflector, which, on the contrary, is occupying a more and more important place.

The reader is here presented with the most recent methods and results needed in the construction of great mirrors for modern reflecting telescopes.

S. P. Langley,

Secretary of the Smithsonian Institution.

Washington, June, 1904.

ON THE CONSTRUCTION

OF A

SILVERED GLASS TELESCOPE,

FIFTEEN AND A HALF INCHES IN APERTURE,

AND

ITS USE IN CELESTIAL PHOTOGRAPHY.

BY

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COMMISSION

TO WHICH THIS PAPER HAS BEEN REFERRED

Prof. Wolcott Gibbs.
Com. J. M. Gilliss, U. S. N.

Joseph Henry,
Secretary S. I.

CONTENTS.

AN ACCOUNT

OF

THE CONSTRUCTION AND USE OF A SILVERED GLASS TELESCOPE.

THE construction of a reflecting telescope capable of showing every celestial object now known, is not a very difficult task. It demands principally perseverance and careful observation of minutiæ. The cost of materials is but trifling compared with the result obtained, and I can see no reason why silvered glass instruments should not come into general use among amateurs. The future hopes of Astronomy lie in the multitude of observers, and in the concentration of the action of many minds. If what is written here should aid in the advance of that noble study, I shall feel amply repaid for my labor.

A short historical sketch of this telescope may not be uninteresting. In the summer of 1857, I visited Lord Rosse's great reflector, at Parsonstown, and, in addition to an inspection of the machinery for grinding and polishing, had an opportunity of seeing several celestial objects through it. On returning home, in 1858, I determined to construct a similar, though smaller instrument; which, however, should be larger than any in America, and be especially adapted for photography. Accordingly, in September of that year, a 15 inch speculum was cast, and a machine to work it made. In 1860, the observatory was built, by the village carpenter, from my own designs, at my father's country seat, and the telescope with its metal speculum mounted. This latter was, however, soon after abandoned, and silvered glass adopted. During 1861, the difficulties of grinding and polishing that are detailed in this account were met with, and the remedies for many of them ascertained. The experiments were conducted by the aid of three $15\frac{1}{2}$ inch disks of glass, together with a variety of smaller pieces. Three mirrors of the same focal length and aperture are almost essential, for it not infrequently happens that two in succession will be so similar, that a third is required for attempting an advance beyond them. One of these was made to acquire a parabolic figure, and bore a power of 1,000. The winter was devoted to perfecting the art of silvering, and to the study of special photographic processes. A large portion of 1862 was spent with a regiment in a campaign in Virginia, and but few photographs were produced till autumn, when sand clocks and clepsydras of several kinds having been made, the driving mechanism attained great excellence. During the winter, the art of local corrections was acquired, and two $15\frac{1}{2}$ inch mirrors, as well as two of 9 inches for the photographic enlarging apparatus, were completed. The greater part of 1863 has been occupied by lunar and planetary photography, and the enlargement of the small negatives obtained at the focus of the great reflector. Lunar negatives have been produced which have been magnified to 3 feet in diameter. I have also finished two mirrors $15\frac{1}{2}$ inches in aperture, suitable for a Herschelian telescope, that is, which can only converge oblique pencils to a focus free from aberration. This work has all been accomplished in the intervals of professional labor.

The details of the preceding operations are arranged as follows: § 1. Grinding and Polishing the Mirrors; § 2. The Telescope Mounting; § 3. The Clock Movement; § 4. The Observatory; § 5. The Photographic Laboratory; § 6. The Photographic Enlarger.

§ 1. GRINDING AND POLISHING THE MIRRORS.

(1.) Experiments on a Metal Speculum.

My first 15 inch speculum was an alloy of copper and tin, in the proportions given by Lord Rosse. His general directions were closely followed, and the casting was very fine, free from pores, and of silvery whiteness. It was 2 inches thick, weighed 110 pounds, and was intended to be of 12 feet focal length. The grinding and polishing were conducted with the Rosse machine. Although a great amount of time was spent in various trials, extending over more than a year, a fine figure was never obtained—the principal obstacle to success being a tendency to polish in rings of different focal length. It must, however, be borne in mind that Lord Rosse had so thoroughly mastered the peculiarities of his machine as to produce with it the largest specula ever made and of very fine figure.

During these experiments there was occasion to grind out some imperfections, $\frac{8}{100}$ of an inch deep, from the face of the metal. This operation was greatly assisted by stopping up the defects with a thick alcoholic solution of Canada balsam, and having made a rim of wax around the edge of the mirror, pouring on nitro-hydrochloric acid, which quickly corroded away the uncovered spaces. Subsequently an increase in focal length of 15 inches was accomplished, by attacking the edge zones of the surface with the acid in graduated depths.

An attempt also was made to assist the tedious grinding operation by including the grinder and mirror in a Voltaic circuit, making the speculum the positive pole. By decomposing acidulated water between it and the grinder, and thereby oxidizing the tin and copper of the speculum, the operation was much facilitated, but the battery surface required was too great for common use. If a sufficient intensity was given to the current, speculum metal was transferred without oxidation to the grinder, and deposited in thin layers upon it. It was proposed at one time to make use of this fact, and coat a mirror of brass with a layer of speculum metal by electrotyping. The gain in lightness would be considerable.

During the winter of 1860 the speculum was split into two pieces, by the expansion in freezing of a few drops of water that had found their way into the supporting case.

(2.) Silvering Glass.

At Sir John Herschel's suggestion (given on the occasion of a visit that my father paid him in 1860), experiments were next commenced with silvered glass specula. These were described as possessing great capabilities for astronomical purposes. They reflect more than 90 per cent. of the light that falls upon them, and only weigh one-eighth as much as specula of metal of equal aperture.

As no details of Steinheil's or Foucault's processes for silvering in the cold way were accessible at the time, trials extending at intervals over four months were made. A variety of reducing agents were used, and eventually good results obtained with milk sugar.

Soon after a description of the process resorted to by M. Foucault in his excellent experiments was procured. It consists in decomposing an alcoholic solution of ammonia and nitrate of silver by oil of cloves. The preparation of the solutions and putting them in a proper state of instability are very difficult, and the results by no means certain. The silver is apt to be soft and easily rubbed off, or of a leaden appearance. It is liable to become spotted from adherent particles of the solutions used in its preparation, and often when dissolved off a piece of glass with nitric acid leaves a reddish powder. Occasionally, however, the process gives excellent results.

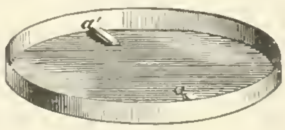
In the winter of 1861, M. Cimeg published his method of silvering looking-glasses by tartrate of potash and soda (Rochelle salt). Since I have made modifications in it fitting the silver for being polished on the reverse side, I have never on any occasion failed to secure bright, hard, and in every respect, perfect films.

The operation, which in many details resembles that of M. Foucault, is divided into: 1st, cleaning the glass; 2d, preparing the solutions; 3d, warming the glass; 4th, immersion in the silver solution and stay there; 5th, polishing. It should be carried on in a room warmed to 70° F. at least. The description is for a $15\frac{1}{2}$ inch mirror.

1st. Clean the glass like a plate for collodion photography. Rub it thoroughly with nitric acid, and then wash it well in plenty of water, and set it on edge on filtering paper to dry. Then cover it with a mixture of alcohol and prepared chalk, and allow evaporation to take place. Rub it in succession with many pieces of cotton flannel. This leaves the surface almost chemically clean. Lately, instead of chalk I have used plain uniodized collodion, and polished with a freshly-washed piece of cotton flannel, as soon as the film had become semi-solid.

2d. Dissolve 560 grains of Rochelle salt in two or three ounces of water and filter. Dissolve 800 grains of nitrate of silver in four ounces of water. Take an ounce of strong ammonia of commerce, and add nitrate solution to it until a brown precipitate remains undissolved. Then add more ammonia and again nitrate of silver solution. This alternate addition is to be carefully continued until the silver solution is exhausted, when some of the brown precipitate should remain in suspension. The mixture then contains an undissolved excess of oxide of silver. Filter. Just before using, mix with the Rochelle salt solution, and add water enough to make 22 ounces.

Fig. 1.



The Silvering Vessel.

The vessel in which the silvering is to be performed may be a circular dish (Fig. 1) of ordinary tinplate, $16\frac{1}{2}$ inches in diameter, with a flat bottom and perpendicular sides one inch high, and coated inside with a mixture of beeswax and rosin (equal parts). At opposite ends of one diameter two narrow pieces of wood, *a a′*, $\frac{1}{8}$ of an inch thick, are cemented. They are to keep the face of the mirror from the bottom of the vessel, and permit of a rocking motion being given to the glass. Before using such a vessel, it is necessary to touch any cracks that may have formed in the wax with a hot poker. A spirit lamp causes bubbles and holes through to the tin. The vessel too must always, especially if partly silvered, be cleaned with nitric acid and water, and left filled with cold water till needed. Instead of the above, India-rubber baths have been occasionally used.

3d. In order to secure fine and hard deposits in the shortest time and with weak solutions, it is desirable, though not necessary, to warm the glass slightly. This is best done by putting it in a tub or other suitably sized vessel, and pouring in water enough to cover the glass. Then hot water is gradually stirred in, till the mixture reaches 100° F. It is also advantageous to place the vessels containing the ingredients for the silvering solution in the same bath for a short time.

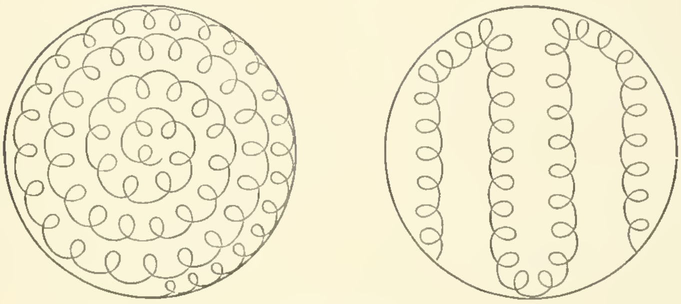
4th. On taking the glass out of the warm water, carry it to the silvering vessel—into which an assistant has just previously poured the mixed silvering solution—and immediately immerse it face downwards, dipping in first one edge and then quickly letting down the other till the face is horizontal. The back of course is not covered with the fluid. The same precautions are necessary to avoid streaks in silvering as in the case of putting a collodion plate in the bath. Place the whole apparatus before a window. Keep up a slow rocking motion of the glass, and watch for the appearance of the bright silver film. The solution quickly turns brown, and the silver soon after appears, usually in from three to five minutes. Leave the mirror in the liquid about six times as long. At the expiration of the twenty minutes or half hour lift it out, and look through it at some very bright object. If the object is scarcely visible, the silver surface must then be washed with plenty of water, and set on edge on bibulous paper to dry. If, on the contrary, it is too thin, put it quickly back, and leave it until thick enough. When polished the silver ought, if held between the eye and the sun, to show his disk of a light blue tint. On coming out of the bath the metallic surface should have a rosy golden color by reflected light.

5th. When the mirror is thoroughly dry, and no drops of water remain about the edges, lay it upon its back on a thoroughly dusted table. Take a piece of the softest thin buckskin, and stuff it loosely with cotton to make a rubber. Avoid using the edge pieces of a skin, as they are always hard and contain nodules of lime.

Go gently over the whole silver surface with this rubber in circular strokes, in order to commence the removal of the rosy golden film, and to condense the silver. Then having put some very fine rouge on a piece of buckskin laid flat on the table, impregnate the rubber with it. The best stroke for polishing is a motion in small circles, at times going gradually round on the mirror, at times across on the various chords (Fig. 2). At the end of an hour of continuous gentle rubbing, with occasional touches on the flat rouged skin, the surface will be polished so as to be perfectly black in oblique positions, and, with even moderate care, scratchless.

The process is like a burnishing. Put the rubber carefully away for another occasion.

Fig. 2.



Polishing Strokes.

The thickness of the silver thus deposited is about $\frac{1}{200,000}$ of an inch. Gold leaf, when equally transparent, is estimated at the same fraction. The actual value of the amount on a $15\frac{1}{2}$ inch mirror is not quite a cent—the weight being less than 4 grains (239 milligrammes on one occasion when the silver was unusually thick), if the directions above given are followed.

Variations in thickness of this film of silver on various parts of the face of the mirror are consequently only small fractions of $\frac{1}{200,000}$ of an inch, and are therefore of no optical moment whatever. If a glass has been properly silvered, and shows the sun of the same color and intensity through all parts of its surface, the most delicate optical tests will certainly fail to indicate any difference in figure between the silver and the glass underneath. The faintest peculiarities of local surface seen on the glass by the method of M. Foucault, will be reproduced on the silver.

The durability of these silver films varies, depending on the circumstances under which they are placed, and the method of preparation. Sulphuretted hydrogen tarnishes them quickly. Drops of water may split the silver off. Under certain circumstances, too, minute fissures will spread all over the surface of the silver, and it will apparently lose its adhesion to the glass. This phenomenon seems to be connected with a continued exposure to dampness, and is avoided by grinding the edge of the concave mirror flat, and keeping it covered when not in use with a sheet of flat plate glass. Heat seems to have no prejudicial effect, though it might have been supposed that the difference in expansibility would have overcome the mutual adhesion.

Generally silvered mirrors are very enduring, and will bear polishing repeatedly, if previously dried by heat. I have some which have been used as diagonal reflectors in the Newtonian, and have been exposed during a large part of the day to the heat of the sun concentrated by the $15\frac{1}{2}$ inch mirror. These small mirrors are never covered, and yet the one now in the telescope has been there a year, and has had the dusty film—like that which accumulates on glass—polished off it a dozen times.

In order to guard against tarnishing, experiments were at first made in gilding silver films, but were abandoned when found to be unnecessary. A partial conversion of the silver film into a golden one, when it will resist sulphuretted hydrogen, can be accomplished as follows: Take three grains of hyposulphite of soda, and dissolve it in an ounce of water. Add to it slowly a solution in water of one grain of chloride of gold. A lemon yellow liquid results, which eventually becomes clear. Immerse the silvered glass in it for twenty-four hours. An exchange will take place, and the film become yellowish. I have a piece of glass prepared in this way which remains unhurt in a box, where other pieces of plain silvered glass have changed some to yellow, some to blue, from exposure to coal gas.

I have also used silvered glass plates for daguerreotyping. They iodize beautifully if freshly polished, and owing probably to the absence of the usual copper alloy of silver plating, take impressions with very short exposures. The resulting picture has a rosy warmth, rarely seen in ordinary daguerreotypes. The only precaution necessary is in fixing to use an alcoholic solution of cyanide of potassium, instead of hyposulphite of soda dissolved in water. The latter has a tendency to split up the silver. The subsequent washing must be with diluted common alcohol.

Pictures obtained by this method will bear high magnifying powers without showing granulation. Unfortunately the exposure required for them in the telescope is six times as great as for a sensitive wet collodion, though the iodizing be carried to a lemon yellow, the bromizing to a rose red, and the plate be returned to the iodine.

(3.) Grinding and Polishing Glass.

Some of the facts stated in the following paragraphs, the result of numerous experiments, may not be new to practical opticians. I have had, however, to polish with my own hands more than a hundred mirrors of various sizes, from 19 inches to $\frac{1}{4}$ of an inch in diameter, and to experience very frequent failures for three years, before succeeding in producing large surfaces with certainty and quickly. It is well nigh impossible to obtain from opticians the practical minutiæ which are essential, and which they conceal even from each other. The long continued researches of Lord Rosse, Mr. Lassell, and M. Foucault are full of the most valuable facts, and have been of continual use.

The subject is divided into: a. The Peculiarities of Glass; b. Emery and Rouge; c. Tools of Iron, Lead and Pitch; d. Methods of Examining Surfaces; e. Machines.

a. *Peculiarities of Glass.*

Effects of Pressure.—It is generally supposed that glass is possessed of the power of resistance to compression and rigidity in a very marked manner. In the course of these experiments it has appeared that a sheet of it, even when very thick, can with difficulty be set on edge without bending so much as to be optically worthless. Fortunately in every disk of glass that I have tried, there is one diameter on either end of which it may stand without harm.

In examining lately various works on astronomy and optics, it appears that the same difficulty has been found not only in glass but also in speculum metal. Short used always to mark on the edge of the large mirrors of his Gregorian telescopes the point which should be placed uppermost, in case they were removed from their cells. In achromatics the image is very sensibly changed in sharpness if the flint and crown are not in the best positions; and Mr. Airy, in mounting the Northumberland telescope, had to arrange the means for turning the lenses on their common axis, until the finest image was attained. In no account, however, have I found a critical statement of the exact nature of the deformation, the observers merely remarking that in some positions of the object glass there was a sharper image than in others.

Before I appreciated the facts now to be mentioned, many fine mirrors were condemned to be re-polished, which, had they been properly set in their mountings, would have operated excellently.

In attempting to ascertain the nature of deformations by pressure, many changes were made in the position of the disk of glass, and in the kind of support. Some square mirrors, too, were ground and polished. As an example of the final results, the following case is presented: A $15\frac{1}{2}$ inch unsilvered mirror $1\frac{1}{4}$ inch thick was set with its best diameter perpendicular, the axis of the mirror being horizontal (Fig. 8). The image of a pin-hole illuminated by a lamp was then observed to be single, sharply defined, and with interference rings surrounding it as at *a*, Fig. 3. On turning the glass 90 degrees, that is one quarter way round, its axis still pointing in the same direction, it could hardly be realized that the same concave surface was converging the rays. The image was separated into two of about equal intensity, as at *b*, with a wing of light going out above and below from the junction. Inside and outside of the focal plane the cone of rays had an elliptical section, the major axis being horizontal inside, and perpendicular outside. Turning the mirror still more round the image gradually improved, until the original diameter was perpendicular again—the end that had been the uppermost now being the lowest. A similar series of changes occurred in supporting the glass on various parts of the other semicircle. It might be supposed that irregularities on the edge of the glass disk, or in the supporting arc would account for the phenomena. But two facts dispose of the former of these hypotheses: in the first place if the glass be turned exactly half way round, the character of the image is unchanged, and it is not to be believed that in many different mirrors this could occur by chance coincidence. In the second place, one of these mirrors has been carefully examined after being ground and polished three times in succession, and on each occasion required the same diameter to be perpendicular. As to the second hypothesis no material difference is observed whether the supporting arc below be large or small, nor when it is replaced by a thin semicircle of tinplate lined with cotton wool.

Fig. 3.

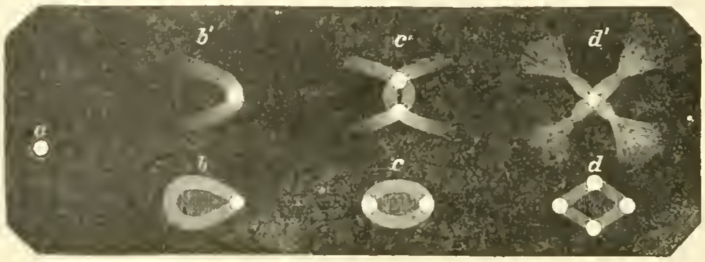
Effect of Pressure on a Reflecting Surface.

I am led to believe that this peculiarity results from the structural arrangement of the glass. The specimens that have served for these experiments have probably been subjected to a rolling operation when in a plastic state, in order to be reduced to a uniform thickness. Optical glass, which may be made by softening down irregular fragments into moulds at a temperature below that of fusion, may have the same difficulty, but whether it has a diameter of minimum compression can only be determined by experiment. Why speculum metal should have the same property might be ascertained by a critical examination of the process of casting, and the effect of the position of the openings in the mould for the entrance of the molten metal.

Effects of Heat.—The preceding changes in glass when isolated appear very simple, and their remedy, to keep the proper diameter perpendicular, is so obvious that it may seem surprising that they should have given origin to any embarrassment. In fact it is now desirable to have a disk in which they are well marked. But in practice they are complicated in the most trying manner with variations produced by heat pervading the various parts of the glass unequally. The following case illustrates the effects of heat:—

A $15\frac{1}{2}$ inch mirror, which was giving at its centre of curvature a very fine image (a, Fig. 4) of an illuminated pin-hole, was heated at the edge by placing the right

Fig. 4.



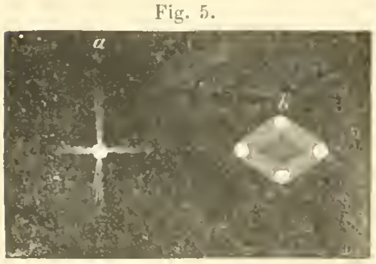
Effects of Heat on a Reflecting Surface.

hand on the back of the mirror, at one end of the horizontal diameter. In a few seconds an arc of light came out from the image as at b', and on putting the left hand on the other extremity of the same diameter the appearance c' was that of two arcs of light crossing each other, and having an image at each intersection. The mirror did not recover its original condition in ten minutes. Another person on a subsequent occasion touching the ends of the perpendicular diameter at the same time that the horizontal were warmed, caused the image d' to become somewhat like two of c', put at right angles to each other. A little distance outside the focus the complementary appearances, b, c, d, were found.

By unsymmetrical warming still more remarkable forms emerged in succession, some of which were more like certain nebulæ with their milky light, than any regular geometrical figure.

If the glass had, after one of these experiments, been immediately put on the polishing machine and re-polished, the changes in surface would to a certain extent have become permanent, as in Chinese specula, and the mirror would have required either re-grinding or prolonged polishing to get rid of them. This occurred unfortunately very frequently in the earlier stages of this series of experiments, and gave origin on one occasion to a surface which could only show the image of a pin-hole as a lozenge (b, Fig. 5), with an image at each angle inside the focus, and as an image a with four wings outside.

Fig. 5.



Effects of Heat rendered permanent.

But it must not be supposed that such apparent causes as these are required to disturb a surface injuriously. Frequently mirrors in the process for correction of spherical aberration will change the quality of their images without any perceptible reason for the alteration. A current of cold or warm air, a gleam of sunlight, the close approach of some person, an unguarded touch, the application of cold water injudiciously will ruin the labor of days. The avoidance of these and similar causes requires personal experience, and the amateur can only be advised to use too much caution rather than too little.

Such accidents, too, teach a useful lesson in the management of a large telescope, never, for instance, to leave one-half the mirror or lens exposed to radiate into cold space, while the other half is covered by a comparatively warm dome. Under the head of the Sun-Camera, some further facts of this kind may be found.

Oblique Mirrors.—Still another propensity of glass and speculum metal must be noted. A truly spherical concave can only give an image free from distortion when it is so set that its optical axis points to the object and returns the image directly back towards it. But I have polished a large number of mirrors in which an image free from distortion was produced *only* when oblique pencils fell on the mirror, and the image was returned along a line forming an angle of from 2 to 3 degrees with the direction of the object. Such mirrors, though exactly suited for the Herschelian construction, will not officiate in a Newtonian unless the diagonal mirror be put enough out of centre in the tube, to compensate for the figure of the mirror. Some of the best photographs of the moon that have been produced in the observatory, were made when the diagonal mirror was 6 inches out of centre in the 16 inch tube. Of course the large mirror below was not perpendicular to the axis of the tube, but was inclined 2° 32′. The figure of such a concave might be explained by the supposition that it was as if cut out of a parabolic surface of twice the diameter, so that the vertex should be on the edge. But if the mirror was turned 180° it apparently did just as well as in the first position, the image of a round object being neither oval nor elliptical, and without wings. The image, however, is never quite as fine as in the usual kind of mirrors. The true explanation seems rather to be that the radius of curvature is greater along one of the diameters than along that at right angles. How it is possible for such a figure to arise during grinding and polishing is not easy to understand, unless it be granted that glass yields more to heat and compression in one direction than another.

After these facts had been laboriously ascertained, and the method of using such otherwise valueless mirrors put in practice as above stated, chance brought a letter of Maskelyne to my notice. He says, "I hit upon an extraordinary experiment which greatly improved the performance of the six-feet reflector" . . . . . It was one made by Short. "As a like management may improve many other telescopes, I shall here relate it: I removed the great speculum from the position it ought to hold perpendicular to the axis of the tube when the telescope is said to be rightly adjusted, to one a little inclined to the same and found a certain inclination of about $2\frac{1}{2}°$ (as I found by the alteration of objects in the finer one of Dollond's best night glasses with a field of 6°), which caused the telescope to show the object (a printed paper) incomparably better than before; insomuch that I could read many of the words which before I could make nothing at all of. It is plain, therefore, that this telescope shows best with a certain oblique pencil of rays. Probably it will be found that this circumstance is by no means peculiar to this telescope." This very valuable observation has lain buried for eighty-two years, and ignorance of it has led to the destruction of many a valuable surface.

As regards the method of combating this tendency, it is as a general rule best to re-grind or rather re-fine the surface, for though pitch polishing has occasionally corrected it in a few minutes, it will not always do so. I have polished a surface for thirteen and a half hours, examining it frequently, without changing the obliquity in the slightest degree.

Glass, then, is a substance prone to change by heat and compression, and requiring to be handled with the utmost caution.

b. *Emery and Rouge.*

In order to excavate the concave depression in a piece of glass, emery as coarse as the head of a pin has been commonly used. This cuts rapidly, and is succeeded by finer grained varieties, till flour emery is reached. After that only washed emeries should be permitted. They are made by an elutriating process invented by Dr. Green.

Five pounds of the finest sifted flour emery are mixed with an ounce of pulverized gum arabic. Enough water to make the mass like treacle is then added, and the ingredients are thoroughly incorporated by the hand. They are put into a deep jar containing a gallon of water. After being stirred the fluid is allowed to come to rest, and the surface is skimmed. At the end of an hour the liquid containing extremely fine emery in suspension is decanted or drawn off with a siphon, nearly down to the level of the precipitated emery at the bottom, and set aside to subside in a tall vessel. When this has occurred, which will be in the lapse of a few hours, the fluid is to be carefully poured back into the first vessel, and the fine deposit in the second put into a stoppered bottle. In the same way by stirring up the precipitate again, emery that has been suspended 30, 10, 3, 1 minutes, and 20, 3, seconds is to be secured and preserved in wide-mouthed vessels.

The quantity of the finer emeries consumed in smoothing a $15\frac{1}{2}$ inch surface is very trifling—a mass of each as large as two peas sufficing.

Rouge, or peroxide of iron, is better bought than prepared by the amateur. It is made by calcining sulphate of iron and washing the product in water. Three kinds are usually found in commerce: a very coarse variety containing the largest percentage of the cutting black oxide of iron, which will scratch glass like quartz; a very fine variety which can hardly polish glass, but is suitable for silver films; and one intermediate. Trial of several boxes is the best method of procuring that which is desired.

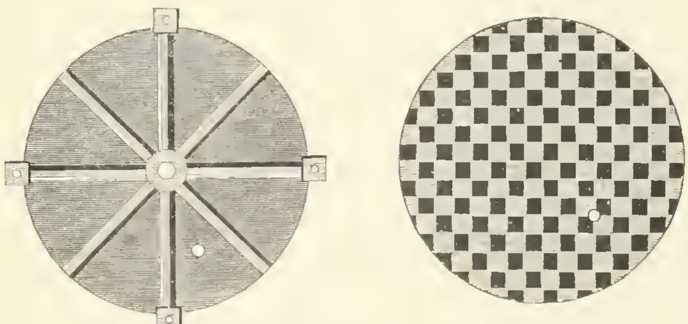
c. *Tools of Iron, Lead, and Pitch.*

In making a mirror, one of the first steps is to describe upon two stout sheets of brass or iron, arcs of a circle with a radius equal to twice the desired focal length, and to secure, by filing and grinding them together, a concave and convex gauge. When the radius bar is very long, it may be hung against the side of a house. By the assistance of these templets, the convex tools of lead and iron and the concave surface of the mirror are made parts of a sphere of proper diameter.

The excavation of a large flat disc of glass to a concave is best accomplished by means of a thick plate of lead, cast considerably more convex than the gauge. The central parts wear away very quickly, and when they become too flat must be made convex again by striking the lead on the back with a hammer. The glass is thus caused gradually to approach the right concavity. Ten or twelve hours usually suffice to complete this stage. The progress of the excavating is tested sufficiently well by setting the convex gauge on a diameter of the mirror, and observing how many slips of paper of a definite thickness will pass under the centre or edge, as the case may be. This avoids the necessity of a spherometer. The thickness of paper is found correctly enough by measuring a half ream, and dividing by the number of sheets. In this manner differences in the versed sine of a thousandth of an inch may be appreciated, and a close enough approximation to the desired focal length reached—the precision required in achromatics not being needed. The preparation of the iron tools on which the grinding is to be finished is very laborious where personal exertion is used. They require to be cast thin in order that they may be easily handled, and hence cannot be turned with very great exactness.

The pair for my large mirrors are $15\frac{1}{2}$ inches in diameter, and were cast $\frac{3}{4}$ of an inch thick, being strengthened however on the back by eight ribs $\frac{3}{4}$ of an inch high, radiating from a solid centre two inches in diameter (*a*, Fig. 6). They weighed 25

Fig. 6.



a *b*

The Iron Grinder.

pounds apiece. Four ears, with a tapped hole in each, project at equal distances round the edge, and serve either as a means of attachment for a counterpoise lever, or as handles.

After these were turned and taken off the lathe chuck, they were found to be somewhat sprung, and had to be scraped and ground in the machine for a week before fitting properly. The slowness in grinding results from the emery becoming imbedded in the iron, and forming a surface as hard as adamant.

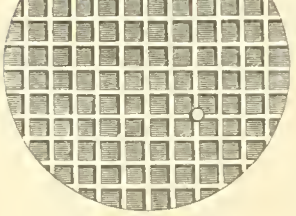
Once acquired, such grinders are very valuable, as they keep their focal length and figure apparently without change if carefully used, and only worked on glass of nearly similar curvature. At first no grooves were cut upon the face, for in the lead previously employed for fining they were found to be a fruitful source of scratches, on account of grains of emery imbedding in them, and gradually breaking loose as the lead wore away. Subsequently it appeared, that unless there was some means of spreading water and the grinding powders evenly, rings were likely to be produced on the mirror, and the iron was consequently treated as follows:—

A number of pieces of wax, such as is used in making artificial flowers, were procured. The convex iron was laid out in squares of $\frac{3}{4}$ of an inch on the side, and each alternate one being touched with a thick alcoholic solution of Canada balsam, a piece of wax of that size was put over it. This was found after many trials to be the best method of protecting some squares, and yet leaving others in the most suitable condition to be attacked. A rim of wax, melted with Canada balsam, was raised around the edge of the iron, and a pint of aqua regia poured in. In a short time this corroded out the uncovered parts to a sufficient depth, leaving an appearance like a chess-board, except that the projecting squares did not touch at the adjoining angles (*b*, Fig. 6). I should have chipped the cavities out, instead of dissolving them away, but for fear of changing the radius of curvature and breaking the thin plate. However as soon as the iron was cleaned, it proved to have become flatter, the radius of curvature having increased $7\frac{3}{4}$ inches. This shows what a state of tension and compression there must be in such a mass, when the removal of a film of metal $\frac{1}{500}$ of an inch thick, here and there, from one surface, causes so great a change.

When the glass has been brought to the finest possible grain on such a grinder, a polishing tool has to be prepared by covering the convex iron with either pitch or rosin. These substances have very similar properties, but the rosin by being clear affords an opportunity of seeing whether there are impurities, and therefore has been frequently used, straining being unnecessary. It is, however, too hard as it occurs in commerce, and requires to be softened with turpentine.

A mass sufficiently large to cover the iron $\frac{1}{8}$ of an inch thick is melted in a porcelain or metal capsule by a spirit lamp. When thoroughly liquid the lamp is blown out, and spirits of turpentine added, a drachm or two at a time. After each addition a chisel or some similar piece of metal is dipped into the fluid rosin, and then immersed in water at the temperature of the room. After a minute or two it is taken out, and tried with the thumb-nail. When the proper degree of softness is obtained, an indentation can be made by a moderate pressure.

Fig. 7.



The Polishing Tool.

The iron having been heated in hot water is then painted in stripes $\frac{1}{8}$ of an inch deep with this resinous composition. The glass concave to be polished being smeared with rouge, is pressed upon it to secure a fit, and the iron is then put in cold water. With a narrow chisel straight grooves are made, dividing the surface into squares of one inch, separated by intervals of one-quarter of an inch (Fig. 7). Under certain circumstances it is also desirable to take off every other square, or perhaps reduce the polishing surface irregularly here and there, to get an excess of action on some particular portion of the mirror.

It is well, on commencing to polish with a tool made in this way, to warm the glass as well as the tool in water (page 4) before bringing the two in contact. If this is not done the polishing will not go on kindly, a good adaptation not being secured for a length of time, and the glass surface being injured at the outset. The rosin on a polisher put away for a day or two suffers an internal change, a species of irregular swelling, and does not retain its original form. Heating, too, has a good effect in preventing disturbance by local variations of temperature in the glass.

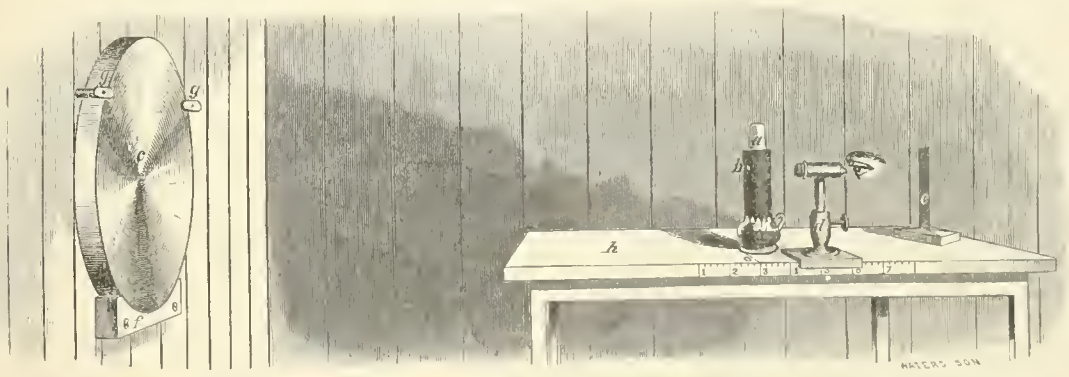
The description of "Local Polishers" will be given under *Machines*.

d. *Methods of Examining Surfaces.*

I have been in the habit of testing mirrors exclusively at the centre of curvature, not putting them in the telescope tube until nearly parabolic or finished. The means of trial are so excellent, the indications obtained so precise, and the freedom from atmospheric disturbances so complete, that the greatest facilities are offered for ascertaining the nature of a surface. In addition the observer is entirely independent of day or night, and of the weather. I do not think that anything more is learned of the telescope, even under favorable circumstances, than in the workshop. For the improvement of these methods of observation, Science is largely indebted to M. Foucault, whose third test—the second in the next paragraph—is sufficient to afford by itself a large part of the information required in correcting a concave surface.

There are two distinct modes of examination: 1st, observing with an eye-piece the image of an illuminated pin-hole at the focus, and the cone of rays inside and outside that plane; 2d, receiving the entire pencil of light coming from the mirror through the pupil on the retina, and noticing the distribution of light and shade, and the appearances in relief on the face of the mirror.

The arrangements for these tests are as follows: Around the flame of a lamp (*a*, Fig. 8.

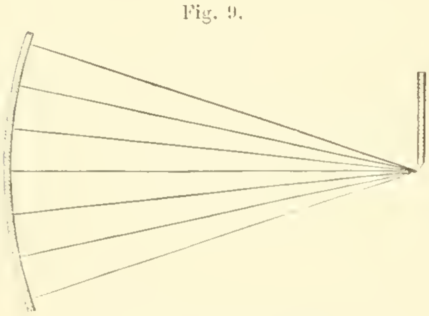


Testing a Concave at the Centre of Curvature.

Fig. 8) a sheet of tin is bent so as to form a cylindrical screen. Through it at the height of the brightest part of the flame, as at *b*, two holes are bored, a quarter of an inch apart, one $\frac{1}{32}$ of an inch in diameter, the other as small as the point of the finest needle will make—perhaps $\frac{1}{200}$ of an inch. This apparatus is to be set at the centre of curvature of the mirror *c*—the optical axis of the latter being horizontal—and so adjusted that the light which diverges from the illuminated hole in use, may, after impinging on the concave surface of the glass, return to form an image close by the side of the tin screen. In the case of the first test, the returning rays are received into an eye-piece or microscope, *d*, magnifying 20 times, and moving upon a divided scale to and from the mirror. In the second test the eye-piece is removed away from before the eye, and a straight-edged opaque screen, *e*, is put in its place. The mirror is supported in these trials by an arc of wood *f*, lined with thick woollen stuff, and above two wooden latches, *g*, *g*, prevent it from from falling forward, but do not compress it. It is, of course, unsilvered. In the figure the table is represented very much closer to the mirror than it should be. In trials on the 15½ inch it has to be 25 feet distant.

The appearance that a truly spherical concave surface presents with the first test is: the image of the hole is sharply defined without any areola of aberration around it, and is surrounded by interference rings. Inside and outside the focus the cone of rays is exactly similar, and circular in section. It presents no trace of irregular illumination, nor any bright or dark circles. With the second test, when the eye is brought into such a position that it receives the whole pencil of reflected rays, and the opaque screen is gradually drawn across in front of the pupil, the brightness of the surface slowly diminishes, until just as the screen is cutting off the last relic of the cone of rays (Fig. 9), the mirror presents an uniform grayish tint, followed by total darkness, and gives to the eye the sensation of a plane.

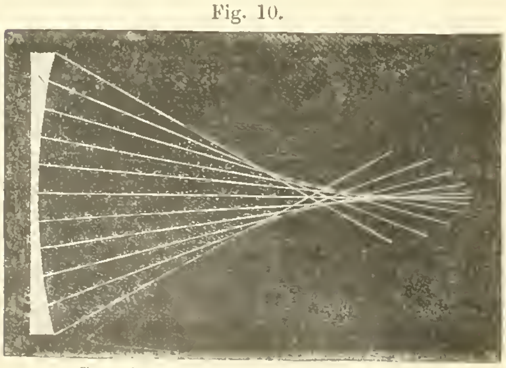
Fig. 9.



Action of the Opaque Screen.

If, however, the mirror is not spherical, but instead gradually *decreases* in focal length toward the edge, the following changes result: The image at the best focus is surrounded by a nebulosity, stronger as the deviation from the sphere is greater, and neither can a sharp focus be obtained nor interference fringes seen. In order to include this nebulosity in the image, it will be necessary to push the eye-piece toward the mirror. Before the cone of rays has completed its convergence, the mass of light will be seen to have accumulated at the periphery, and after the focus is past and divergence has commenced, the accumulation will be around the axis. That is, a caustic (Fig. 10) is formed with its summit from the mirror. By the second test, in gradually eclipsing the light coming from the mirror, just before all the rays are obstructed, a part of those which have constituted the nebulosity will escape past the screen (Fig. 11) into the eye, and cause there an extremely exaggerated appearance in relief of the solid superposed upon the

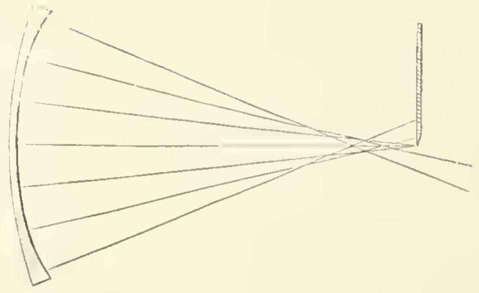
Fig. 10.



Caustic of Oblate Spheroidal Mirror.

true surface beneath. The glass will no longer seem to be a plane, but to have a section as in Fig. 12. Let us examine by the aid of M. Foucault's diagrams why it is that the surface seems thus curved. If the dotted line, Fig. 13, represents the section of the mirror, and the solid line a section of a spherical mirror of the same mean focal length, it will be seen that the curves touch at two points, but are separated by an interval elsewhere. If this interval be projected by means of the differences of the ordinates, the resulting curve will be found to be the same as that which the mirror apparently has.

Fig. 11.

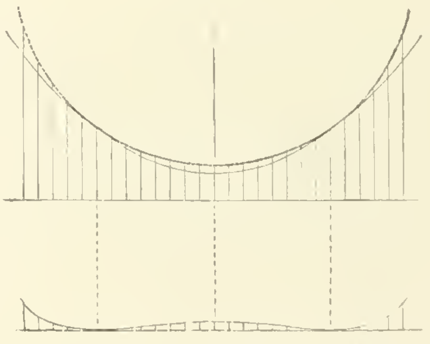


Action of the Opaque Screen.

Fig. 12.

Apparent Section of Oblate Spheroidal Mirror.

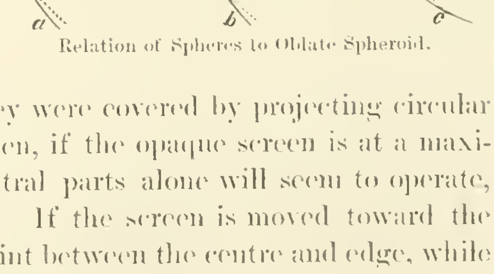
Fig. 13.



Section of Spherical and Spheroidal Mirrors.

If the opaque screen be drawn a short distance from the mirror, the appearance of the section curve will seem to change, the bottom of the groove (Fig. 12) between the centre and edge advancing inwards, and the mound in the middle growing smaller. If the screen be pushed toward the mirror the reverse takes place, the central mound becoming larger, but the edge decreasing. The reason for these variations becomes apparent by considering the three diagrams, Fig. 14. The dotted curve in each instance represents the real curve of the mirror described in the last paragraph, while the solid lines are circles drawn with radii progressionally shorter in *a*, *b* and *c*, and represent sections of three spherical mirrors whose focal lengths also progressively shorten.

Fig. 14.

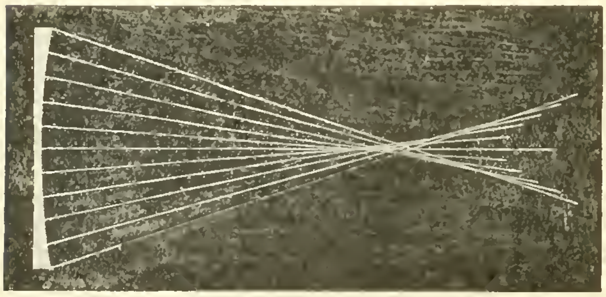


Relation of Spheres to Oblate Spheroid.

When the opaque screen is at a given distance from the mirror under examination, the only parts of the mirror which can officiate well are those which have a curvature corresponding to a radius equal to the same distance. All the other parts seem as if they were covered by projecting circular masses. In looking at Fig. 14, it is plain, then, if the opaque screen is at a maximum distance from the mirror, that the central parts alone will seem to operate, because the two curves (*a*) only touch there. If the screen is moved toward the mirror the curves (*b*) will coincide at some point between the centre and edge, while if carried still farther in only the edges touch and the appearance will be as if a large mound were fixed upon the centre. I have been careful in explaining how a surface may thus seem to present entirely different characteristics if examined from points of view which vary slightly in distance, because a knowledge of these facts is of the utmost importance in correcting such an erroneous figure. It is now obvious that the correction will be equally effectual if the mirror be polished with a small rubber on the edge, or on the centre, or partly on each. The only difference in the result will be, that the mean focal length will be increased in the first instance, and decreased in the second, while it will remain unchanged in the third.

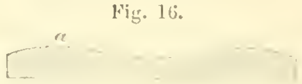
If the mirror, instead of having a section like that of an oblate spheroid, should have either an ellipse, parabola, or hyperbola, as its section curve, the appearances seen above are reversed. Whilst by the first test there is still an aberration round the image at the best focus, the eye-piece must now be drawn from the mirror to include it. The cone of rays is most dense round the axis inside, and at the periphery outside the focus, and the summit of the caustic (Fig. 15) is turned towards the mirror. The second test shows a section as in Fig. 16, a depression at the centre, and the edges turned backwards. The nature of the movement necessary to reduce the surface to a sphere is very plainly indicated, action on a zone a between the centre and edge. If, however, a parabolic section is required, the zone a must not be entirely removed, and the surface rendered apparently flat, but as much of it must be left as experience shows to be desirable.

Fig. 15.



Caustic of Hyperbolic Mirror.

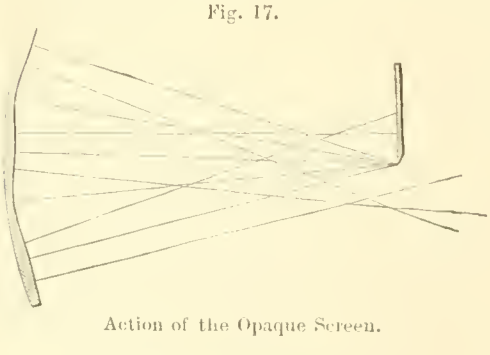
Fig. 16.



Apparent Section of Hyperbolic Mirror.

If, in still a fourth instance, the mirror is not formed by the revolution of any regular curve upon its axis, but has upon its surface zones of longer and shorter radius intermixed irregularly, a very common case, the two tests still indicate with precision the parts in fault, and the correction demanded. Thus the mirror seen in section in Fig. 17, when the principal mass of light was obstructed by the opaque screen, would still permit that coming from certain parts to find its way into the eye.

Fig. 17.



Action of the Opaque Screen.

Figure 18 represents an irregular mirror, that was produced in the process of correction of a hyperbolic surface, which had an apparent section like Fig. 16 previously. The zone a had been acted upon with a small local polisher, and the mirror was finished by subsequently softening down b and c with a larger tool.

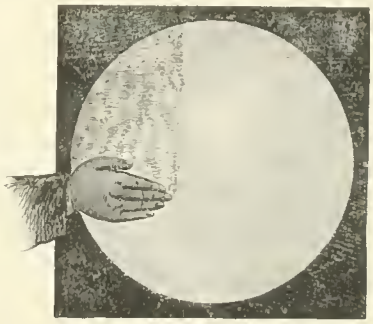
Fig. 18.

Apparent Section of Mirror with Rings.

After having gained from the preceding paragraphs a general idea of the value and nature of these tests at the centre of curvature, a more particular description of their use is desirable. M. Foucault in his methods first brings the mirror to a spherical surface, and then by moving the luminous pin-hole toward the mirror, and correspondingly retracting the eye-piece or opaque screen, carries it, avoiding aberration continually by polishing, through a series of ellipsoidal curvatures, advancing step by step toward the paraboloid of revolution. The length of the apartment, however, soon puts a termination to this gradual system of correction, and he is forced to perform the last steps of the conversion by an empirical process, and eventually to resort to trial in the telescope.

With my mirrors of 150 inches focal length, demanding from the outset a room more than 25 feet long, this successive system had to be abandoned. It was not found feasible to place the lamp in the distant focus of the ellipse—the workshop being less than 30 feet long—and putting the luminous source on stands outside, introduced several injurious complications, not the least of which was currents in the layers of variously refracting air in the apartment. In a still room the density and hygrometric variations in its various parts only give rise to slight embarrassment. The moment, however, that currents are produced, satisfactory examination of a mirror becomes difficult. The air is seen only too easily to move in great spiral convolutions between the mirror and the eye, areolæ of aberration appear around a previously excellent image, and were it not for the second test, any determination of surface would be impossible. By that test the real deviations from truth of figure can be distinguished from the atmospheric, and to a practised eye sufficient indications of necessary changes given. Such a movement as that caused by placing the hand in or under the line of the converging rays, will completely destroy the beauty of an image, and by the second test give origin in the first case to the appearance Fig. 19. In order to be completely exempt at all times from aërial difficulties, it is desirable to have control of a long underground apartment, the openings of which can be tightly closed. As no artificial warmth is needed, there is the minimum of movement in the inclosed air, and conclusions respecting a surface may be arrived at in a very short time. The mirror may also be supported from the ground, so that tremulous vibrations which weary the eye, and interfere with the accuracy of criticism, may be avoided.

Fig. 19.



Atmospheric Motions.

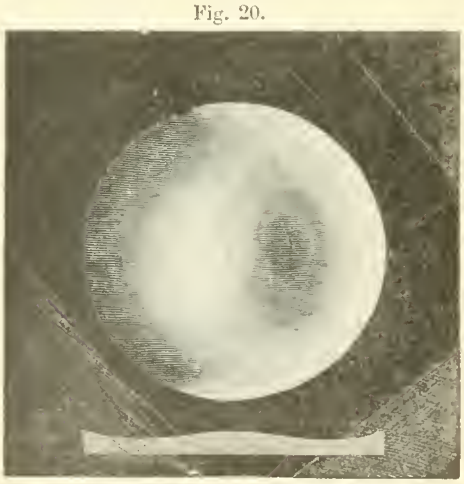
Driven then from observing an image kept continually free from aberration, through advancing ellipsoidal changes, it became necessary to study the gradual increase of deformation, produced by the greater and greater departures from a spherical surface, as the parabola was approached. It was found that a sufficient guide is still provided in these tests, by modifying them properly.

The longitudinal aberration of a mirror of small angular opening is easily calculated—being equal to the square of half the aperture, divided by eight times the principal focal length. That is, if a $15\frac{1}{2}$ inch mirror of 150 inches focal length were spherical, and were used to converge parallel rays, those from its edge would reach a focus $\frac{5}{100}$ of an inch nearer the mirror than those from its central parts. If now the converse experiment be tried, and a mirror of the same size and focal length which can converge parallel rays, falling on all its parts, to one focus, be examined at the centre of curvature, it gives there an amount of longitudinal aberration $\frac{10}{100}$ of an inch, equal to twice the preceding. This latter, then, is the condition at the centre of curvature, to which such mirror must be brought in order to converge parallel rays with exactness. In addition, strict watch must be kept upon the zones intermediate between the centre and edge, both by measurement with diaphragms of their aberration, and better yet, by observation of the regularity of the curve of that apparent solid, Fig. 16, seen by the second test.

This modification of the first test is literally a method of parabolizing by measure, and is capable of great precision when the eye learns to estimate where the exact focus of a zone is. The little irregularities found round the edges of the holes through the tin screen, Fig. 8, are in this respect of material assistance. They show, too, the increased optical or penetrating power that is gained by increase of aperture. Minute peculiarities, not visible under very high powers with a 10 inch diaphragm, become immediately perceptible even with less magnifying when the whole aperture is used, provided the mirror is spherical.

In the use of the second test precautions have to be taken, as may be inferred from page 15, to set the opaque screen exactly in the proper position. The best method for ascertaining its location is, having received the image into the eye, placed purposely too near the mirror, to cause the screen to move across the cone of rays from the right towards the left side. A jet black shadow begins to advance at the same time, and in the same direction across the mirror. If the eye is then moved from the mirror sufficiently, this black shadow can be made to originate by the same motion of the screen as before, from the left or opposite side of the mirror. Midway between these extremes there is a point where the advance is from neither side. This is the true position for the screen when it is desired to see the imperfections of the surface in highly exaggerated relief, as in Fig. 20, which represents the appearance of Fig. 12.[1]

Fig. 20.



Adjusting the Opaque Screen.

The interpretation of the lights and shadows upon the face of a mirror in this test is always easy, and the observer is not likely to mistake an elevation for a depression, if he bears in mind the fact that the surface under

[1] In order to examine Fig. 20, the book should be held with the left side of the page toward a window or lamp. The eye should also be at least two feet distant. The centre will then be seen to protrude, and the surface present the apparent section engraved below it.

examination must always be regarded as illuminated by an oblique light coming from a source on the side opposite to that from which the screen advances, coming for instance from the left hand side, in the above description.

In practice, the diaphragms commonly used for a $15\frac{1}{2}$ inch mirror have been as small as the light from the unsilvered surface would allow. A six inch aperture at the centre, a ring an inch wide round the edge, and a two inch zone midway between the two.

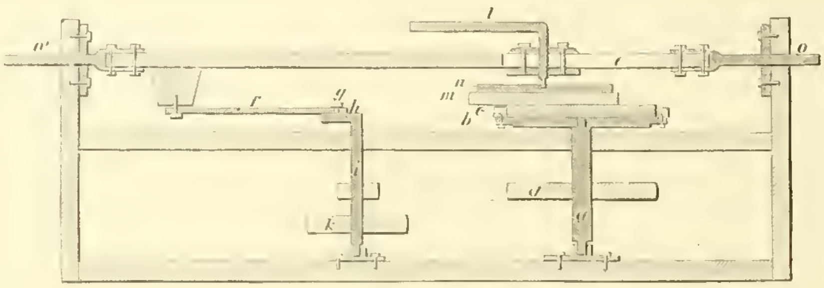
e. *Machines.*

In the beginning of this section the difficulties into which I fell with Lord Rosse's machine were stated. These caused it at the time to be abandoned. A machine based on the same idea as Mr. Lassell's beautiful apparatus was next constructed. It varied, however, in this, that the hypocycloidal curve was described partly by the rotation of the mirror, and partly by the motions of the polisher—the axes of the spindles carrying the two being capable either of coincidence or lateral separation to a moderate extent. A great deal of time and labor was expended in grinding and polishing numerous mirrors with it, but still the difficulty that had been so annoying in the former machine persisted. Frequently, in fact generally, from six to eight zones of unequal focal length were visible, although on some occasions when the mirror was hyperbolic, the number was reduced to two. At first it was supposed that the fault lay with the polishing, the pitch accumulating irregularly from being of improper softness, for it was found to be particularly prone to heap up at the centre. But after I had introduced a method of fine grinding with elutriated hone powder, which enabled the glass to reflect light before the pitch polishing, it became evident that the zones were connected with the mode of motion of the mechanism. Many changes were made in the speed of its various elements, and a contrivance to control the irregular motion of the polisher introduced, but a really fine and uniform parabolic surface was never obtained, the very best showing when finished zones of different focal lengths. Although it cannot be said that I have tried this machine thoroughly, for Mr. Lassell has produced specula of exquisite defining power with it, and must have avoided these imperfections to a great extent, yet the evident necessity of complicating the movement[1] considerably, to avoid the polishing in rings, led me to adopt an entirely different construction, which was used until quite recently. Although it has now been replaced by another machine, which is still better in principle, and gives fine results much more quickly, yet as it produced one parabolic surface that bore a power of more than 1000, and as it serves to introduce the process of grinding, it is worthy of description. The action of machines for grinding and polishing has been thoroughly examined in my workshop, no less than seven different ones having been made at various times.

[1] Messrs. De La Rue and Nasmyth, who used one of Mr. Lassell's machines, as I have since learned, met with the same trouble, and were led to make two additions to the mechanism: 1, to control the rotation of the polisher rigorously; and 2, to give the whole speculum a lateral motion, by which the intersecting points of the curves described by the polisher were regularly changed in distance from the centre of the mirror. Mr. Lassell had previously, however, introduced a contrivance for this latter purpose himself.

The machine, which is a simplification of Lord Rosse's, was intended to give spiral strokes. It differed from the original, however, in demanding a changeable stroke, and in the absence of the lateral motion. In another most essential feature it varied from both that and Mr. Lassell's, *the mirror was always uppermost while polishing*, and being uncounterpoised escaped to as great an extent as possible from the effects of irregular pressure. To any one who has studied the deformations of a reflecting surface, and knows how troublesome it is to support a mirror properly, the advantage is apparent.

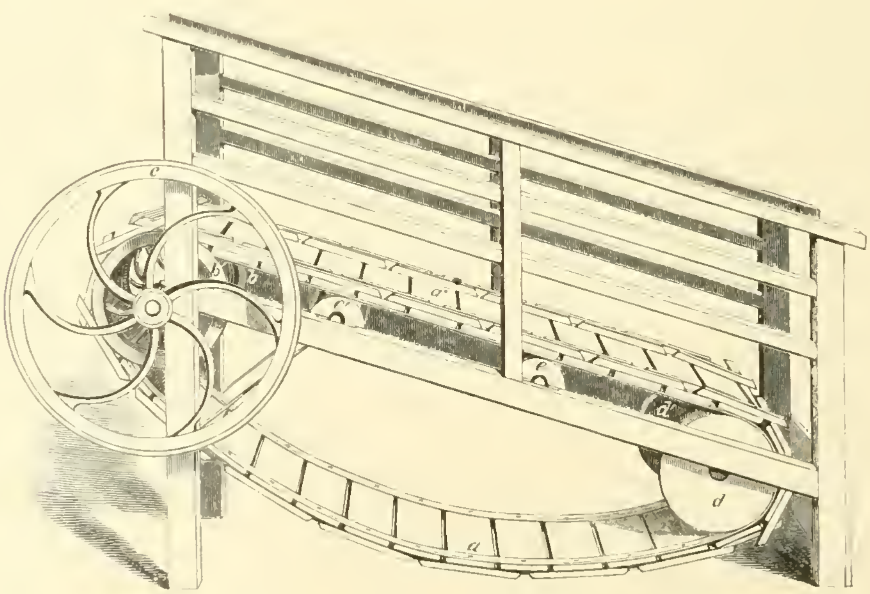
Fig. 21.



Polishing Machine.

The construction is as follows: A stout vertical shaft, *a*, Fig. 21, carries at its top a circular table *b*, upon which the polisher *c* is screwed. Below a band-wheel *d* is fixed. Above the table, at a distance of four inches, a horizontal bar *e* is arranged, so as to move back and forward in the direction of its length, and to carry with it by means of a screw *l*, the mirror *m*, and its iron back or chuck *n*. The bar is moved by a connecting rod *f*, attached to it at one end, and at the other to a pin *g*

Fig. 22.



The Foot Power.

moving a slot. This slot is in a crank *h*, carried by a vertical shaft *i*, near the former one *a*. The band-wheel *k* is connected with the foot power, Fig. 22. The machine, except those parts liable to wear by friction, is made of wood. The ends *o o'* of the horizontal bar *c*, are defended by brass tubes working in mahogany, and have even now but little shake, though many hundred thousands of reciprocations have been made.

The foot power consists of an endless band with wooden treads *a a'*, passing at one end of the apparatus over iron wheels *b b'*, which carry the band-wheel *c* upon their axle. At the other end it goes over the rollers *d d'*. Two pairs of intermediate wheels *e e'*, serve to sustain the weight of the man or animal working in it. The treads are so arranged that they interlock, and form a platform, which will not yield downwards. Owing to its inclination when a weight is put on the platform *a'*, it immediately moves from *b* toward *d* and the band-wheel turns. By a moderate exertion, equivalent to walking up a slight incline at a slow rate, a power more than sufficient to polish a $15\frac{1}{2}$ inch mirror is obtained. This machine, in which very little force is lost in overcoming friction, is frequently employed for dairy use, and is moved commonly in the State of New York by a sheep. I have generally myself walked in the one used by me, and have travelled some days, during five hours, more than ten miles.

In order to give an idea of the method of using a grinding and polishing machine, the following extract from the workshop note-book is introduced:—

"A disk of plate glass $15\frac{1}{2}$ inches in diameter, and $1\frac{1}{4}$ inch thick was procured. It had been polished flat on both sides, so that its internal constitution might be seen.[1] It was fastened upon the table *b* of the machine, by four blocks of wood as at *e*, Fig. 21. Underneath the glass were three thick folds of blanket, 15 inches in diameter, to prevent scratching of the lower face, and avoid risk of fracture. A convex disk of lead weighing 40 pounds having been cast, was laid upon the upper surface of the glass, and then the screw *l* was depressed so as to catch in a perforated iron plate *n*, at the back of the lead *m*, and press downward strongly.

"Emery as coarse as the head of a pin having been introduced, through a hole in the lead, motion was commenced and continued for half an hour, an occasional supply of emery being given. The machine made 150 eight-inch cross strokes, and the mirror 50 revolutions per minute. The grinder *m* was occasionally restrained from turning by the hand. At the end of the time the detritus was washed away, and an examination with the gauge made. A spot 11 inches in diameter, and $\frac{1}{60}$ of an inch deep, was found to have been ground out. The same process was continued at intervals for ten hours, measurements with the gauge being frequently made. The concave was then sufficiently deep. The leaden grinder was kept of the right convexity by beating it on the back when necessary. A finer variety of coarse emery, and after that flour emery were next put on, each for an hour. These left the surface moderately smooth, and nearly of the right focal length. The leaden grinder was then dismissed, and the iron one, Fig. 6, put in its stead. The

[1] The glass that I have used has generally been such as was intended for dead-lights and sky-lights in ships.

mirror was removed from its place, and ground upon a large piece of flat glass for ten minutes, to produce a circular outline to the concavity. It was cemented with soft pitch to the concave iron disk, the counterpart of Fig. 6, and again recentred on the blanketed table *b*. Emeries of 3 and 20 seconds, and 1, 3, 10, 30, 60 minutes' elutriation were worked on it, an hour each. The rate of cross motion was reduced to 25 per minute to avoid heating, the mirror still revolving once for every three cross strokes. The screw pressure of *l* was stopped. This produced a surface exquisitely fine, semi-transparent, and appearing as if covered with a thin film of dried milk. It could reflect the light from objects outside the window until an incidence of 45 degrees was reached, and at night was found to be bright enough for a preliminary examination at the centre of curvature.

"The polisher was constructed in the usual way (page 12), and being smeared with rouge was fastened to the table *b*, where the mirror had been. The latter warmed in water to 120° F., was then put face downwards upon the former, and the screw *l* so lowered as to cause no pressure. The machine was allowed to make 20 four-inch cross strokes per minute, and the polisher to revolve once for every three strokes. The mirror being unconstrainedly supported on the polisher, was irregularly rotated by hand, or rather prevented from rotating with the polisher. The tendency of this method is to produce an almost spherical surface. To change it to a paraboloid, it was only necessary when the glass was polished all over to increase the length of the stroke to 8 inches, and continue working fifteen minutes at a time, examining in the intervals by the tests at the centre of curvature. The production of a polish all over occupied about two hours, but the correction of figure took more time, on account of the frequent examinations, and the absolute necessity of allowing the mirror to come back to a state of equilibrium from which it had been disturbed when worked on the machine." I have seen a mirror which was parabolic when just off the machine, by cooling over night become spherical. And these heat changes are often succeeded by other slower molecular movements, which continue to modify a surface for many days after.

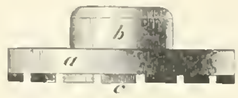
This correction, where time and not length of stroke is the governing agent, has once or twice been accomplished in fifteen minutes, but sometimes has cost several hours. If the figure should have become a hyperboloid of revolution, that is, have its edge zones too long in comparison with the centre, it is only necessary to shorten the stroke to bring it back to the sphere, or even to overpass that and produce a surface in which at the centre of curvature the edge zones have too short a focal length (Fig. 12).

Very much less trouble from zones of unequal focal length was experienced after this machine and system of working were adopted. This was owing probably partly to the element of irregularity in the rotation of the mirror, and partly to the fact that the surface is kept spherical until polished, and is then rapidly changed to the paraboloid. Where the adjustments of an apparatus are made so as to attempt to keep a surface parabolic for some hours, there is a strong tendency for zones to appear, and of a width bearing a fixed relation to the stroke.

The method of producing reflecting surfaces next to be spoken of, is however that which has finally been adopted as the best of all, being capable of forming mirrors which are as perfect as can be, and yet only requiring a short time. It is the correction of a surface by local retouches. In the account published by M. Foucault, it appears that he is in France the inventor of this improvement.

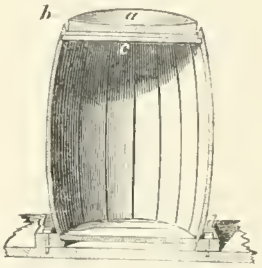
The mode of practising the retouches is as follows: Several disks of wood, as *a*, Fig. 23, varying from 8 inches to ½ an inch in diameter, are to be provided, and covered with pitch or rosin of the usual hardness, in squares as at *c*, on one side.[1] On the other a low cylindrical handle *b* is to be fixed. The mirror *a*, Fig. 24, having been fined with the succession of emeries before described, is laid face upward on several folds of blanket, arranged upon a circular table, screwed to an isolated post in the centre of the apartment, which permits the operator to move completely round it. An ordinary barrel has generally supplied the place of the post, the head *c*, Fig. 24, serving for the circular table, and the rim *b* preventing the mirror sliding off. The other end is fastened to the floor by four cleets *d d'*.

Fig. 23.



Local Polisher.

Fig. 24.



Section of Optician's Post.

The large polisher is first moved over the surface in straight strokes upon every chord, and a moderate pressure is exerted. As soon as the mirror is at all brightened, perhaps in five minutes, the operation is to be suspended, and an examination at the centre of curvature made. By carefully turning round, the best diameter for support is to be found, and marked with a rat-tail file on the edge, and then the curve of the mirror ascertained. If it is nearly spherical, as will be the case if the grinding has been conducted with care and irregular heating avoided, it is to be replaced on the blanketed support, and the previous action kept up until a fine polish, free from dots like stippling, is attained. This stage should occupy three or four hours. Another examination should reveal the same appearances as the preceding. It is next necessary to lengthen the radius of curvature of the edge zones, or what is much better shorten that of the centre, so as to convert the section curve into a parabola. This is accomplished by straight strokes across every diameter of the face, at first with a 4 inch, then with a 6 inch, and finally with the 8 inch polisher. Examinations must, however, be made every five or ten minutes, to determine how much lateral departure from a direct diametrical stroke is necessary, to render the curve uniform out to the edge. Care must be taken always to warm the polisher, either in front of a fire or over a spirit lamp, before using it.

Perhaps the most striking feature in this operation is that the mirror presents continually a curve of revolution, and is not diversified with undulations like a ruffle. By walking steadily round the support, on the top of which the mirror is placed, there seems to be no tendency for such irregularities to arise.

If the correction for spherical aberration should have proceeded too far, and the mirror become hyperbolic, the sphere can be recovered by working a succession

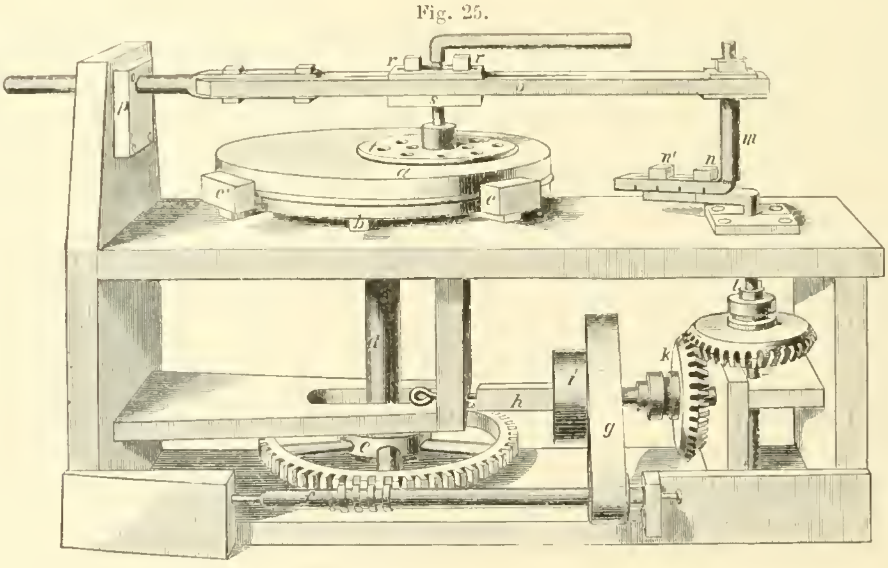
[1] M. Foucault used plano-convex lenses of glass, of a radius of curvature slightly less than that of the mirror, and covered with paper on the convex face.

of polishers of increasing size on the zone *a*, Fig. 16, intermediate between the centre and edge, causing their centres to pass along every chord that can be described tangent to the zone.

A most perfect and rapid control can thus be exercised over a surface, and an uniform result very quickly attained. It becomes a pleasant and interesting occupation to produce a mirror. But two effects have presented themselves in this operation, which unfortunately bar the way to the very best results. In the first place the edge parts of such mirrors, for more than half an inch all around, bend backwards and become of too great focal length, and the rays from these parts cannot be united with the rest forming the image. In the second place, the surface, when critically examined by the second test, is found to have a delicate wavy or fleecy appearance, not seen in machine polishing.[1] Although the variations from the true curve implied by these latter greatly exaggerated imperfections are exceedingly small, and do not prevent a thermometer bulb in the sunshine appearing like a disk surrounded by rings of interference, yet they must divert some undulations from their proper direction, or else they would not be visible. All kinds of strokes have been tried, straight, sweeping circular, hypocycloidal, &c. without effecting their removal. M. Foucault, who used a paper polisher, also encountered them. Eventually they were imputed to the unequal pressure of the hand, and in consequence a machine to overcome the two above mentioned faults of manual correction was constructed.

The mirror *a*, is carried by an iron chuck or table *b*, covered with a triple

Fig. 25.



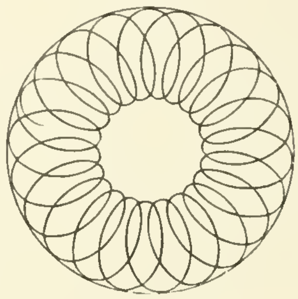
Machine for Local Corrections.

fold of blanket, and is prevented from slipping off by four cleets *c c'*. The vertical shaft *d* passes through a worm-wheel *e*, the endless screw of which *f*, is driven by a band *g*, from the primary shaft *h*. At *i* is the band-wheel for connection to

[1] By this it is not meant that there is a rippled polish, like that produced by buckskin.

the foot-power. At one end of the primary shaft is firmly fixed the cogwheel *k*, which drives the crank-shaft *l*. Attached to the horizontal part of *l*, is the crank-pin *m*. The two bolts *n n′* move in a slot, so that the crank-pin may be set at any distance from 0 to 2 inches, out of line with *l*. Above, the crank-pin carries one end of the bar *o*, the other end passing through an elliptical hole in the oak-block *p*. Down the middle of the bar runs a long slot, through which the screw-pin *q* passes, and which permits *q* to be brought over any zone from the centre to the edge of the mirror *a*. It is retained by the bolts *r r′*, which are tapped into *s*. The local polisher is seen at *t*. The curve which the centre of the local polisher describes upon the face of the mirror, varies with the adjustments. Fig. 26 is a reduction from one traced by the machine, the overlapping being seen on the left side. The mirror is not tightly confined by the cleets *c c′*, for that would certainly injure the figure, but performs a slow motion of rotation, so that in no two successive strokes are the same parts of the edge pressed against them.

Fig. 26.



Hypocycloidal Curve.

The local polishers are made of lead, alloyed with a small proportion of antimony, and are 8, 6, and 4 inches in diameter, respectively. The largest and smallest are most used, the former on account of its size polishing most quickly, but the latter giving the truest surface. The rosin that covers them is just indentable by the thumb nail, and is arranged in a novel manner. The leaden basis, as seen at *t*, Fig. 25, is perforated in many places with holes, which permit evaporation, serve for the introduction of water where needed, and allow the rosin to spread freely. Grooves are made from one aperture to another, and the rosin thus divided into irregular portions. The effects of the production of heat are in this way avoided.

The mirror may be ground and fined on this machine, in the same manner as on that described at page 21, or it may be ground with a small tool 8 inches in diameter, as recently suggested by M. Foucault, the results in the latter case being just as good a surface of revolution as in the former. It is best polished with the 8 inch, and a moderate pressure may be given by the screw *q*, if the pitch is not too soft. This, however, tends to leave an excavated place at the centre of the mirror, the size depending on the stroke of the crank *m*, which should be about 2 inches. The pin *q* ought to be half way from the centre to the edge of the mirror, but must be occasionally moved right or left an inch along the slot. When the surface is approaching a perfect polish, the warmed 4 inch polisher must be put in the place of the 8 inch. The pin *q* must be set exactly half-way between the centre and edge of the mirror, and the crank must have a stroke of two inches radius. The polisher then just goes up to the centre of the glass surface with one edge, and to the periphery with the other, while the outer excursion of the inner edge and inner excursion of the outer edge meet, and neutralize one another at a midway point. Wherever the edge of a polisher changes direction many times in succession, on a surface, a zone is sure to form, unless avoided in this manner. All the foregoing description is for a $15\frac{1}{2}$ inch mirror.

By this system of local polishing the difficulties of heat, distribution of polishing powders, irregular contact of the rosin, &c. that render the attainment of a fine figure so uncertain usually, entirely disappear. A spherical surface is produced as above described, and afterwards by moving q towards the edge, and at the same time increasing the stroke, it is converted into a paraboloid. The fleecy appearance spoken of on a former page is not perceived, and the surface is good almost up to the extreme edge.

(4.) Eye-Pieces, Plane Mirrors and Test Objects.

The telescope is furnished with several eye-pieces of various construction, giving magnifying powers from 75 to 1200, or if it were desired even higher. For the medium powers 300 and 600 Ramsden, or rather positive eye-pieces have been adopted. They differ, however, from the usual form in being achromatic, that is, each plano-convex is composed of a flint and crown, arranged according to formulas calculated by Littrow. In this way a large flat field and absence of color are secured, and the fine images yielded by the mirror are not injured. For the higher powers, single achromatic lenses are used, and for the highest of all a Ross microscope.

With these means it has been found that the parabolic surfaces yielded by the processes before described, will define test objects excellently. Of close double stars they will separate such as γ^2 Andromedæ, and show the colors of the components. In the case of unequal stars which seem to be more severe tests, they can show the close companion of Sirius—discovered by Mr. Alvan Clark's magnificent refractor—the sixth component of θ^1 Orionis, and a multitude of other difficult objects.

As an example of light collecting power, Debillisima between ε and 5 Lyræ is found to be quintuple, as first noticed by Mr. Lassell. In the $18\frac{1}{2}$ inch specula of Herschel, it was only recorded as double, and, according to Admiral Smyth, Lord Rosse did not notice the fourth and fifth components. Jupiter's moons show with beautiful disks, and their difference in diameter is very marked. As for the body of that planet, it is literally covered with belts up to the poles. The bright and dark spots on Venus, and the fading illumination of her inner edge, and its irregularities are perceived even when the air is far from tranquil. Stars are often seen as disks, and without any wings or tails, unless indeed the mirror should be wrongly placed, so that the best diameter for support is not in the perpendicular plane, passing through the axis of the tube.

It has been found that no advantage other than the decrease of atmospheric influence on the image, results from cutting down the aperture of these mirrors by diaphragms, while the disadvantage of reducing the separating power, is perceived at the same time. Faint objects can be better seen with the whole surface than with a reduced aperture, and this though apparently a property common to all reflectors and object glasses is not so in reality. A defective edge will often cause the whole field to be filled with a pale milky light, which will extinguish the fainter stars. Good definition is just as important for faint as for close objects.

The properties of these mirrors have been best shown by the excellence of the photographs taken with them. Although these are not as sharp as the image seen in the telescope, yet it must not be supposed that an imperfect mirror will give just as good pictures. A photograph which is magnified to 3 feet, represents a power of 380. As the original negative taken at the focus of the mirror is not quite $1\frac{1}{2}$ inch in diameter when the moon is at its mean distance, it has to be enlarged about 25 times, and has therefore to be very sharp to bear it.

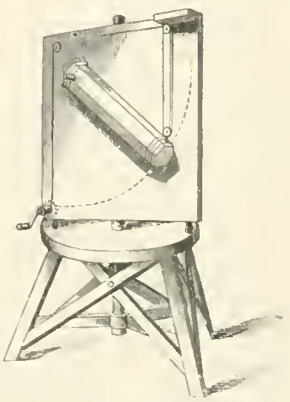
The light collecting power of an unsilvered mirror is quite surprising. With a $15\frac{1}{2}$ inch, the companion of α Lyræ can be perceived, though it is only of the eleventh magnitude. The moon and other bright objects are seen with a purity highly pleasing to the eye, some parts being even more visible than after silvering.

In order to finish this description, one part more of the optical apparatus requires to be noticed—the plane mirrors. In the Newtonian reflector the image is rejected out at the side of the tube by a flat surface placed at 45° with the optical axis of the large concave.[1] If this secondary mirror is either convex or concave, it modifies the image injuriously, causing a star to look like a cross, and this though the curvature be so slight as hardly to be perceptible by ordinary means. For a long time I used a piece 3×5 inches, which was cut from the centre of a large looking-glass accidentally broken, but eventually found that by grinding three pieces of 6 inches in diameter against one another, and polishing them on very hard pitch, a nearer approach to a true plane could be made. They were tested by being put in the telescope, and observing whether the focus was lengthened or shortened, and also by trial on a star. When sufficiently good to bear these tests, a piece of the right size was cut out with a diamond, from the central parts.

§ 2. THE TELESCOPE MOUNTING.

The telescope is mounted as an altitude and azimuth instrument, but in a manner that causes it to differ from the usual instrument of that kind. The essential feature is, that *the eye-piece or place of the sensitive plate is stationary at all altitudes*, the observer always looking straight forward, and never having to stoop or assume inconvenient and constrained positions.

Fig. 27.



Miss Herschel's Telescope.

The stationary eye-piece mounting was first used by Miss Caroline Herschel, who had a 27 inch Newtonian arranged on that plan. Fig. 27. (Smyth's Celestial Cycle.)

Subsequently it was applied to a large telescope by Mr. Nasmyth, the eminent engineer, but no details of his construction have reached me. He used it for making drawings of the moon, which are said to be excellently executed.

When it became necessary to determine how my telescope should be mounted, I was strongly urged to make it

[1] A right-angled prism cannot be used with advantage to replace the plane silvered mirrors, because it transmits less light than they reflect, is more liable to injure the image, and the glass is apt to be more or less colored. Its great size and cost, one three inches square on two faces being required for my purposes, has also to be considered.

an equatorial. But after reflecting on the fact that it was intended for photography, and that absolute freedom from tremor was essential, a condition not attained in the equatorial when driven by a clock, and in addition that in the case of the moon rotation upon a polar axis does not suffice to counteract the motion in declination, I was led to adopt the other form.

A great many modifications of the original idea have been made. For instance, instead of counterpoising the end of the tube containing the mirror by extending the tube to a distance beyond the altitude or horizontal axis, I introduced a system of counterpoise levers which allows the telescope to work in a space little more than its own focal length across. This construction permits both ends of the tube to be supported, the lower one on a wire rope, and gives the greatest freedom from tremor, the parts coming quickly to rest after a movement. In the use of the telescope for photography, as we shall see, the system of bringing the mass of the instrument to complete rest before exposing the sensitive plate, and only driving that plate itself by a clock, is always adopted.

The obvious disadvantage connected with the alt-azimuth mounting—the difficulty of finding some objects—has not been a source of embarrasment. In fact the instability of the optical axis in reflecting instruments, if the mirror is unconstrainedly supported, as it should be, renders them unsuitable for determinations of position. A little patience will enable an observer to find all necessary tests, or curious objects.

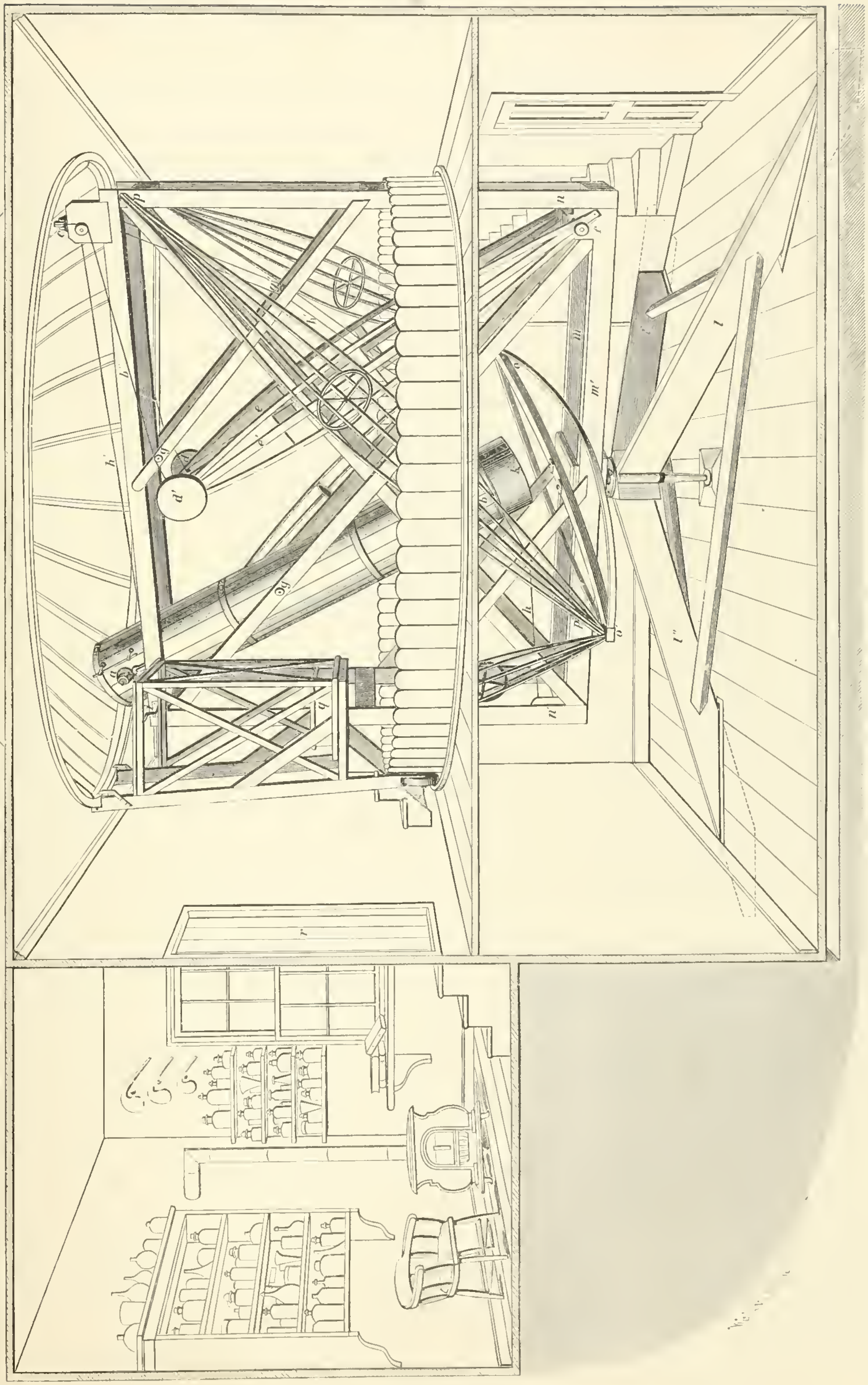
The mounting is divided into: a. The Tube; and b. The supporting frame.

a. *The Tube.*

The telescope tube is a sixteen sided prism of walnut wood, 18 inches in diameter, and 12 feet long. The staves are $\frac{3}{8}$ of an inch thick, and are hooped together with four bands of brass, capable of being tightened by screws. Inside the tube are placed two rings of iron, half an inch thick, reducing the internal diameter to about 16 inches. At opposite sides of the upper end of the tube are screwed the perforated trunnions *a*, Fig. 28 (of which only one is shown), upon which it swings. Surrounding the other end is a wire rope $b\ b'\ b''$, the ends of which go over the pulleys *c* (c' not shown) on friction rollers, and terminate in disks of lead $d\ d'$. These counterpoises are fastened on the ends of levers $e\ e'$, which turn below on a fixed axle *f*.

By this arrangement as the tube assumes a horizontal position and becomes, so to speak, heavier, the counterpoises do the same, while when the tube becomes perpendicular, and most of its weight falls upon the trunnions, the counterpoises are carried mostly by their axle. A continual condition of equilibrium is thus reached, the tube being easily raised or depressed to any altitude desired. It is necessary, however, to constrain the wire rope $b\ b'\ b''$, to move in the arc of the circle described by the end of the tube and ends of the levers and hence the twelve rollers or guide pulleys $g\ g'\ g''$. Over some of the same pulleys a thin wire rope $h\ h'$ runs, but while its ends are fastened to the lower part of the tube at *h*, the central parts go twice around a roller connected with the winch *i*, near the eye-piece, thus enabling the observer to move the telescope in altitude, without taking the eye from the eye-piece

Fig. 28.

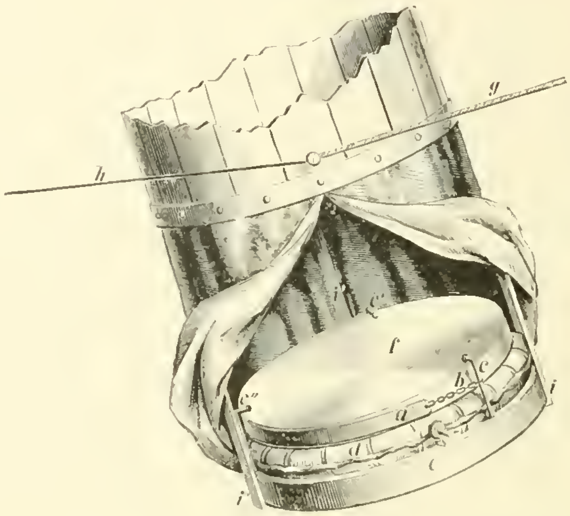


Sectional View of Observatory.

The iron wire rope required to be carefully made, so as to avoid rigidity. It contains $2\frac{1}{3}$ miles of wire, $\frac{1}{100}$ of an inch in diameter, and has 300 strands. Each single wire will support 7 pounds It is, however, more flexible than a hempen rope of the same size, owing to its loose twisting.

At the lower end of the tube, at the distance of a foot, and crossing it at right angles, held by three bars of iron $i\ i'\ i''$, Fig. 29, is a circular table of oak e, which

Fig. 29.



The Mirror Support.

carries an India-rubber air sac d, and upon this the mirror f is placed. The edge support of the mirror is furnished by a semicircular band of tin-plate a, lined inside with cotton, and fastened at the ends by links of chain b, (b' not seen) to two screws $c\ c'$; g and h are the wire ropes, marked b and h in Fig. 28.

Instead of the blanket support which Herschel found so advantageous, M. Foucault has suggested this use of an air sac. In his instrument there is a tube going up to the observer, by which he may adjust its degree of inflation. It requires that there should be three bearings $c\ c'\ c''$, in front of the mirror, against which it may press when the sac behind is inflated, otherwise the optical axis is altogether too instable, and objects cannot be found. The arrangement certainly gives beautiful definition, bringing stars to a disk when the glass just floats, without touching its front bearings. The first sac that I made was composed of two circular sheets of India-rubber cloth, joined around the edges. But this could not be used while photographing, because the image was kept in a state of continuous oscillation if there was a breeze, and even under more favorable circumstances took a long time to come to rest. It was not advisable to blow the mirror hard up against its three front bearings, in order to avoid the instability, for then every point in of an object became triple. To the eye the oscillations were not offensive, because the swaying image was sharp.

Subsequently, however, an air chair cushion was procured, and as the surface was flat instead of convex the difficulty became so much less, that the blanket support was definitely abandoned. It is necessary that the mirror should have free play in the direction of the length of the tube when this kind of support is used, and that is the reason why the tin edge hoop must terminate in links of chain.

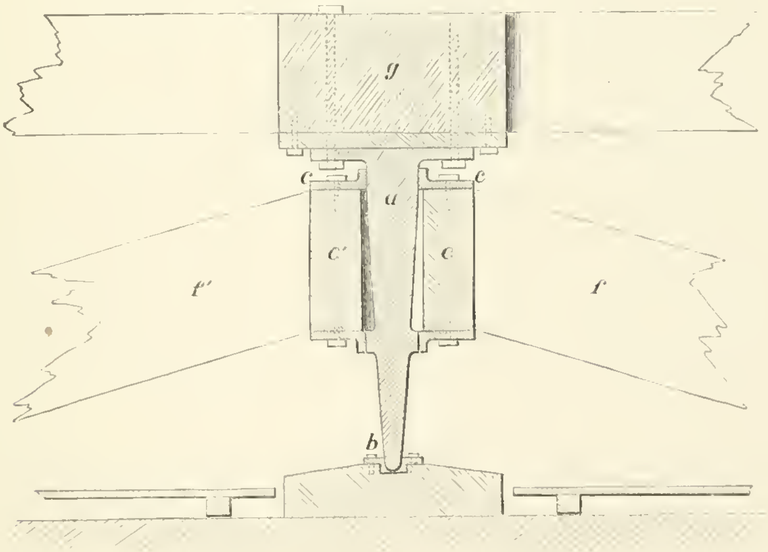
The interval, eight or ten inches, which separates the face of the mirror from the tube, is occupied by a curtain of black velvet, confined below by a drawing cord and tacked above to the tube. This permits access to the mirror to put a glass cover on it, and when shut down stops the current of air rushing up. When the instrument is not being used this curtain is left open, because the mirror and tube are in that case kept more uniform in temperature with the surrounding air.

In spite of such contrivances there is still sometimes a strong residual current in the tube. I have tried to overcome it by covering the mouth of the tube with a sheet of flat glass, but have been obliged to abandon that because the images were injured. At one time, too, when it was supposed that the current was partly from the observer's body, heated streams of air going out around the tube, the aperture in the dome was closed by a conical bag of muslin, which fitted the mouth of the telescope tightly. The only advantages resulting were mere bodily comfort and a capability of perceiving fainter objects than before, because the sky-light was shut off.

b. *The Supporting Frame.*

The frame which carries the preceding parts is of wood, and rests on a vertical axis *a*, Fig. 30, turning below in a gun-metal cup *b*, supported by a marble block

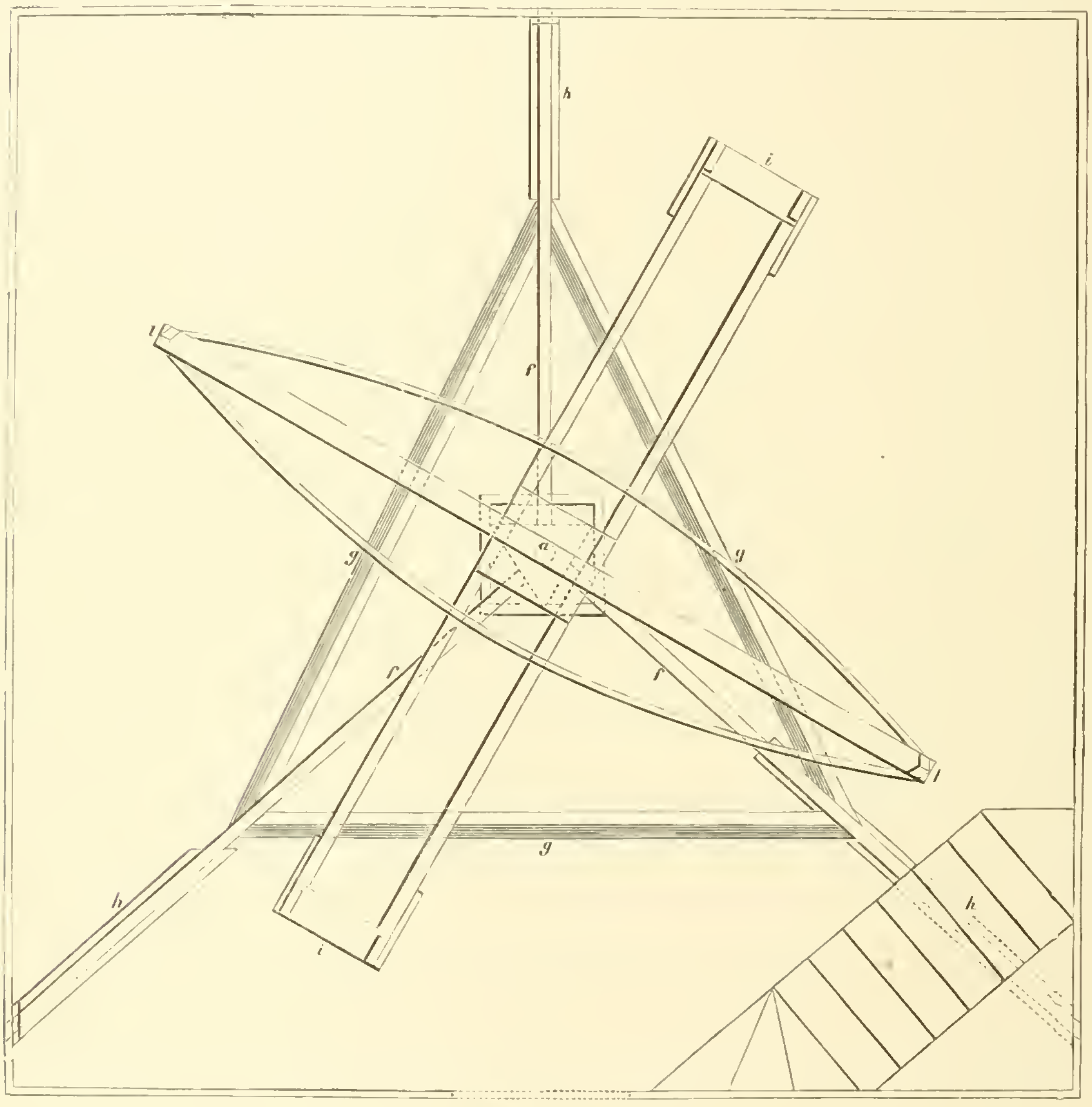
Fig. 30.



Section of Azimuth Axis.

resting on the solid rock. The upper end of the axis is sustained by two collars, one $c\,c'$ above, and the other below an intermediate triangular box $c\,c'$ from the sides of which three long beams $f\,f\,f$ 12×3 inches diverge, gradually declining till they meet the solid rock at the limits of the excavation in which the observatory is placed. These beams are fastened together by cross-pieces *g g g*, Fig. 31, and go through the floor in spaces *h h h*, so contrived that the floor does not touch them. At the ends they are cased with a thick leaden sheathing, to deaden vibration and prevent the access of moisture.

Fig. 31.



Plan of Observatory (lower floor).

This tripod support in connection with the sustaining of the telescope by the wire rope, gives that steadiness which is so essential in photography. Only a slight amount of force, about two pounds, is required to move the instrument in azimuth, though it weighs almost a thousand pounds.

The plan of the frame centrally carried by the axis *a* is as follows: From the corners of a parallelogram *i i* (2 × 13 feet) of wooden beams, eight inches thick and three inches broad, perpendiculars *n n'*, Fig. 28, rise. At the top they are connected by lighter pieces to form a parallelogram, similar to that below, and just large enough to contain the tube of the telescope. At right angles to the parallelogram below, and close upon it, a braced bar *o o'*, Fig. 28, crosses. From its extremities four slanting braces as at *p p'*, Fig. 28, go to the corners of the upper parallelogram, and combine to give it lateral support. At the top of one close pair of the perpendiculars *n'*, Fig. 28, are bronze frames carrying friction rollers upon which the trunnions move, while similarly upon the other pair *n* are two pulleys, also on friction rollers, for the wire rope coming from the counterpoises.

Movement in altitude is very easily accomplished, and with the left hand upon the winch *i*, under high powers, both altitude and azimuth motions are controlled, and the right hand left free. The whole apparatus works so well, that in ordinary observation the want of a clock movement has not been felt. Of course for photography that is essential.

§ 3. THE CLOCK MOVEMENT.

The apparatus for following celestial bodies is divided into two parts; a. The Sliding Plate-holder; and b. The Clepsydra. In addition a short description of the Sun-Camera, c, is necessary.

a. *The Sliding Plate-holder.*

Mr. De La Rue, who has done so much for celestial photography, was the first to suggest photographing the moon on a sensitive plate, carried by a frame moving in the apparent direction of her path. He never, however, applied an automatic driving mechanism, but was eventually led to use a clock which caused the whole telescope to revolve upon a polar axis, and thus compensate for the rotation of the earth, and on certain occasions for the motion of the moon herself. In this way he has produced the best results that have been obtained in Europe. Lord Rosse, too, employed a similar sliding plate-holder, but provided with clock-work to move it at an appropriate rate. I have not been able as yet to procure any precise account of either of these instruments.

The first photographic representations of the moon ever made, were taken by my father, Professor John W. Draper, and a notice of them published in his quarto work "On the Forces that Organize Plants," and also in the September number, 1840, of the London, Edinburgh, and Dublin Philosophical Magazine. He presented the specimens to the New York Lyceum of Natural History. The Secretary of that Association has sent me the following extract from their minutes:—

"*March 23d*, 1840. Dr. Draper announced that he had succeeded in getting a representation of the moon's surface by the Daguerreotype . . . . . The time occupied was 20 minutes, and the size of the figure about 1 inch in diameter. Daguerre had attempted the same thing, but did not succeed. This is the first time that anything like a distinct representation of the moon's surface has been obtained.

"ROBT. H. BROWNNE, *Secretary*."

As my father was at that time however much occupied with experiments on the Chemical Action of Light, the Influence of Light on the Decomposition of Carbonic Acid by Plants, the Fixed Lines of the Spectrum, Spectrum Analysis, &c., the results of which are to be found scattered through the Philosophical Magazine, Silliman's Journal, and the Journal of the Franklin Institute, he never pursued this very promising subject. Some of the pictures were taken with a three inch, and some with a five inch lens, driven by a heliostat.

In 1850, Mr. Bond, taking advantage of the refractor of 15 inches aperture at Cambridge, obtained some fine pictures of the moon, and subsequently of double stars, more particularly Mizar in Ursa Major. The driving power, in this instance, was also applied to move the telescope upon a polar axis.

Besides these, several English and continental observers, Messrs. Hartnup, Phillips, Crookes, Father Secchi, and others, have worked at this branch of astronomy, and, since 1857, Mr. Lewis M. Rutherfurd, of New York, has taken many exquisite lunar photographs, which compare favorably with foreign ones.

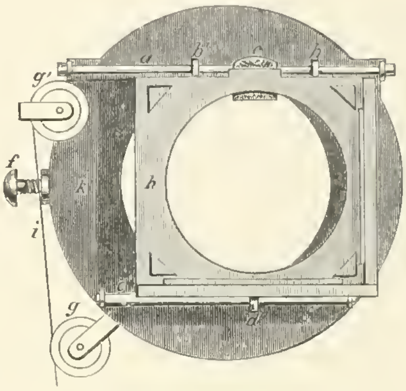
But in none of these instances has the use of the sliding plate-holder been persisted in, and its advantages brought into view. In the first place it gets rid completely of the difficulties arising from the moon's motion in declination, and in the second, instead of injuring the photograph by the tremors produced in moving the whole heavy mass of a telescope weighing a ton or more, it only necessitates the driving of an arrangement weighing scarcely an ounce.

My first trials were with a frame to contain the sensitive plate, held only at three points. Two of these were at the ends of screws to be turned by the hands, and the third was on a spring so as to maintain firm contact. This apparatus worked well in many respects, but it was found that however much care might be taken, the hands always caused some tremor in the instrument. It was evident then that the difficulty from friction which besets the movements of all such delicate machinery, and causes jerking and starts, would have to be avoided in some other way.

I next constructed a metal slide to run between two parallel strips, and ground it into position with the greatest care. This, when set in the direction of the moon's apparent path, and moved by one screw, worked better than the preceding. But it was soon perceived that although the strips fitted the frame as tightly as practicable, an adhesion of the slide took place first to one strip and then to the other, and a sort of undulatory or vermicular progression resulted. The amount of deviation from a rectilinear motion, though small, was enough to injure the photographs. At this stage of the investigation the regiment of volunteers to which I belonged was called into active service, and I spent several months in Virginia.

My brother, Mr. Daniel Draper, to whose mechanical ingenuity I have on several occasions been indebted for assistance in the manifold difficulties that have arisen while constructing this telescope, continued these experiments at intervals. He presented me on my return with a slide and sand-clock, with which some excellent photographs have been taken. He had found that unless the slide above mentioned was made ungovernably long, the same trouble continued. He then ceased catching the sliding frame *h*, Fig. 32, by two opposite sides, and made it run along a single steel rod *a*, being attached by means of two perforated plates of brass *b*, *b'*. The cord *i* going to the sand-clock, was applied so as to pull as nearly as possible in the direction of the rod. A piece of cork *c*, gave the whole steadiness, and yet softness of motion. The lower end of the frame was prevented from swinging back and forward by a steel pin d, which played along the glass rod e. All these parts were attached to a frame k, fitting on the eyepiece holder, and permitting the rod a to change from the horizontal position in which it is here drawn, to any angular one desired. The thumb-screw f retained it in place; g and g' are pulleys which permit the cord to change direction.

Fig. 32.

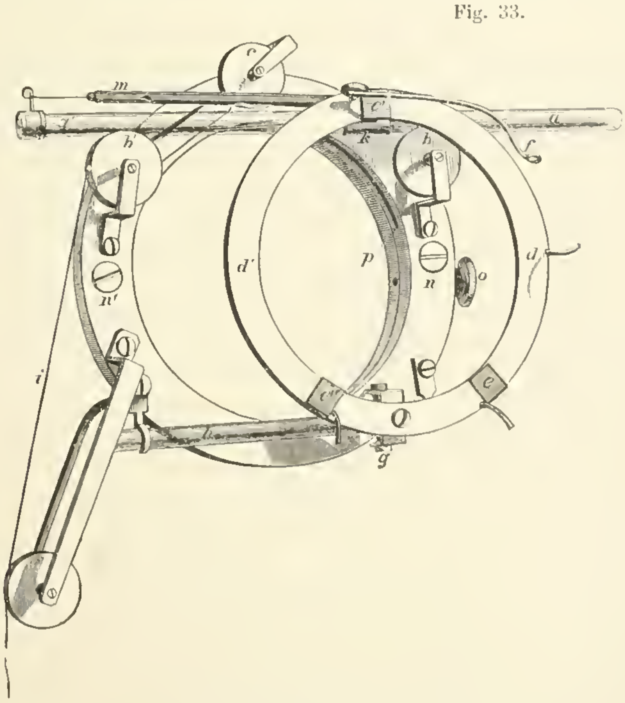


Sliding Plate-holder.

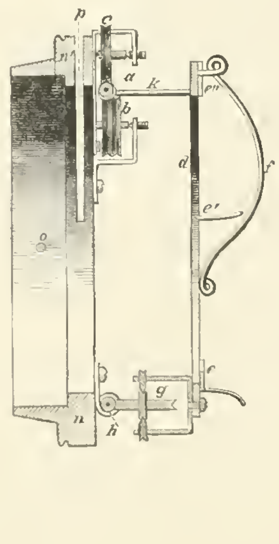
Subsequently, a better method of examining the uniformity of the rate, than by noticing the sharpness of the photograph produced, was invented. It consists in arranging a fixed microscope, magnifying about 40 times, at the back of the ground glass plate, which fits in the same slide as the sensitive plate. By watching the granulated appearance pass before the eye, as the slide is moved by the clock, the slightest variation from uniformity, any pulsatile or jerking movement is rendered visible. By the aid of this microscopic exaggeration, it was seen that occasionally, when there had been considerable changes in temperature, the steadiness of the motion varied. This was traced to the irregular slipping of b, b'.

A different arrangement was then adopted, by which a lunar crater can be kept bisected as long as is necessary, and which gives origin to no irregularities, but pursues a steady course. The principle is, not to allow a slipping friction anywhere, but to substitute rolling friction, upon wheels turning on points at the ends of their axles. The following wood-cut is half the real size of this arrangement.

Fig. 33.



Frictionless Slide (front view).



Sectional view.

A glass rod *a*, *a'*, Fig. 33, is sustained by two wheels *b*, *b'*, and kept in contact with them by a third friction roller *c*, pressed downward by a spring. This rod carries a circular frame *d*, *d'*, upon which at *e*, *e'*, *e''*, are three glass holders and platinum catches. A spring *f* holds the sensitive plate in position, by pressing against its back. The circular frame *d* is kept in one plane by a fourth friction roller *g*, which runs on a glass rod *h*, and is kept against it by the inward pressure of the overhanging frame *d*. The cord *i* is attached to the arm *k*, and pulls in the direction of the glass rod *a*. From *m* to a fixed point near *b*, a strip of elastic India-rubber is stretched, to keep the cord tight. The ring of brass *n*, *n'* carries the whole, serving as a basis for the stationary parts, and in its turn being fastened to the eyepiece holder, so as to allow the glass rod *a* to change direction, and be brought into coincidence with the apparent path of the moon. At *o* is a thumb-screw or clamp Through the ring *n*, *n'*, a groove *p* is cut, into which a piece of yellow glass may be placed, when the actinic rays are to be shut off from the plate.

Since this contrivance has been completed, all the previous difficulties have vanished. The moving of a plate can be accomplished with such precision, that when the atmosphere was steady, negatives were taken which have been enlarged to three feet in diameter.

The length of time that such a slide can be made to run is indefinite, depending in my case on the size of the diagonal flat mirror, and aperture of the eyepiece holder. I can follow the moon for nearly four minutes, but have never required to do so for more than fifty seconds. At the mouth of the instrument, where no secondary mirror is necessary, the time of running could be increased.

The setting of the frictionless slide in angular position is accomplished as follows: A ground glass plate is put into it, with the ground face toward the mirror. Upon this face a black line must have been traced, precisely parallel to the rod *a*. This may be accomplished by firmly fixing a pencil point against the ground side, and then drawing the frame *d* and glass past it, while the rest of the slide is held fast. As the moon passes across the field, the position of the apparatus must be changed, until one of the craters runs along the line from end to end. A cross line drawn perpendicular to the other, serves to adjust the rate of the clepsydra as we shall see, and when a crater is kept steadily on the intersection for twice or three times the time demanded to secure an impression, the adjustment may be regarded as complete.

It is necessary of course to expose the sensitive plate soon after, or the apparent path of the moon will have changed direction, unless indeed the slide is set to suit a future moment.

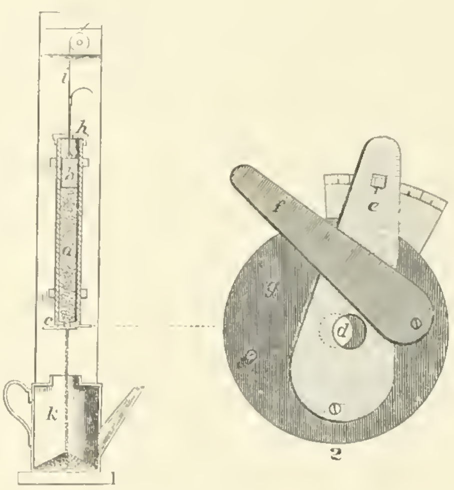
b. *The Clepsydra.*

My prime mover was a weight supported by a column of sand, which, when the sand was allowed to run out through a variable orifice below, could be made to descend with any desired velocity and yet with uniformity. In addition, by these means an unlimited power could be brought to bear, depending on the size of the weight. Previously it was proposed to use water, and compensate for the decrease in flow, as the column shortened, by a conical vessel; but it was soon perceived that as each drop of water escaped from the funnel-shaped vessel, only a corresponding weight would be brought into play. This is not the case with sand, for in this instance every grain that passes out causes the whole weight that is supported by the column to come into action. In the former instance a movement consisting of a series of periods of rest and periods of motion occurs, because power has to accumulate by floating weight lagging behind the descending water, and then suddenly overtaking it. In the latter case, on the contrary, there is a regular descent, all minor resistances in the slide being overcome by the steady application of the whole mass of the weight.

When these advantages in the flow of sand were ascertained, all the other prime movers were abandoned. Mercury-clocks, on the principle of the hydrostatic paradox, air-clocks, &c., in great variety, had been constructed.

The sand-clock consisted of a tube *a* (Fig. 34), eighteen inches long and one and a half in diameter, nearly filled with sand that had been raised to a bright red heat and sifted. Upon the top of the sand a leaden weight *b* was placed. At the bottom of the tube a peculiar stopcock, seen at (2) enlarged, regulated the flow, the amount passing depending on the size of the aperture *d*. This stopcock consisted of two thin plates, fixed at one end and free at the other. The one marked *e* is the adjusting lever, and its aperture moves past that in the plate *g*. The lever *f* serves to turn the sand off altogether, without disturbing the size of the other aperture, which, once set to the moon's rate, varies but slightly in short times. A movable cover *h*, perforated to allow the cord *i* to pass through, closed the top, while the vessel *k* retained the escaped sand, which at suitable times was returned into the tube *a*, the weight *b* being temporarily lifted out. From the clock the cord *i* communicated motion to the frictionless slide, as shown in Fig. 33. This cord should be as inelastic as possible, consistent with pliability, and well waxed.

Fig. 34.



The Sand-Clock.

One who has not investigated the matter would naturally suppose that the flow of sand in such a long tube would be much quicker when the tube was full than when nearly empty, and that certainly that result would occur when a heavy weight was put on the shifting mass. But in neither case have I been able to detect the slightest variation, for, although by shaking the tube a diminution of the space occupied by the sand may be caused, yet no increase of weight tried could accomplish the same reduction. These peculiarities seem to result from the sand arching as it were across the vessel, like shot in a narrow tube, and only yielding when the under supports are removed. In blasting, a heavy charge of gunpowder can be retained at the bottom of a hole, and made to split large masses of rock, by filling the rest of the hole with dry sand.

I believe that no prime mover is more suitable than a sand-clock for purposes where steady motion and a large amount of power are demanded. The simplicity, for instance, of a heliostat on this plan, the large size it might assume, and its small cost, would be great recommendations. In these respects its advantages over wheelwork are very apparent. The precision with which such a sand-clock goes may be appreciated when it is stated, that under a power of 300 a lunar crater can be kept bisected for many times the period required to photograph it. To secure the greatest accuracy in the rate of a sand-clock, some precautions must be taken. The tube should be free from dents, of uniform diameter, and very smooth or polished inside. Water must not be permitted to find access to the sand, and hygrometric varieties of that substance should be avoided, or their salts washed out. The sand should be burned to destroy organic matter, and so sifted as to retain grains nearly equal in size. The weight, which may be of lead, must be turned so as to go easily down the tube, and must be covered with writing paper or some other hard and smooth material, to avoid the proneness to adhesion of sand. A long bottle filled with mercury answers well as a substitute.

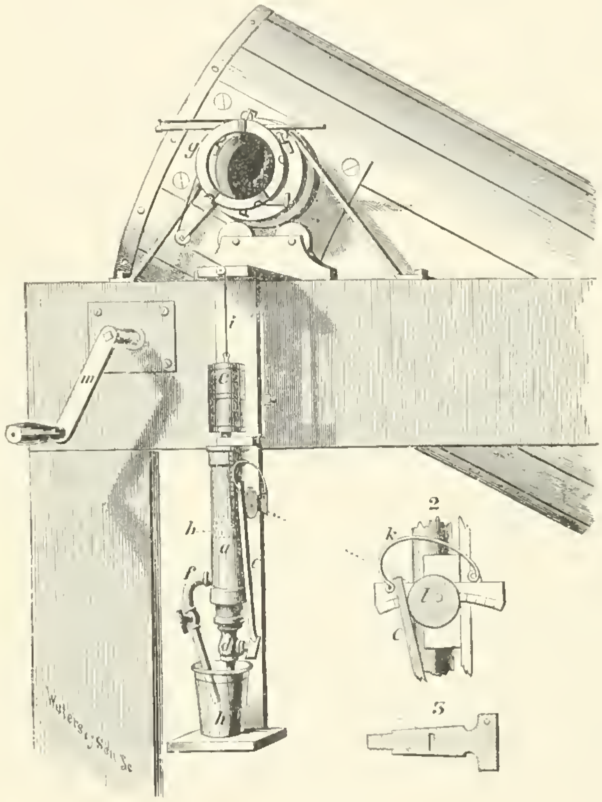
I have used in such clocks certain metallic preparations: Fine shot, on account of its equality of size, might do for a very large clock with a considerable opening below, but is unsuitable for a tube of the size stated above. There is, however, a method by which lead can be reduced to a divided condition, like fine gunpowder, when it may replace the sand. If that metal is melted with a little antimony, and while cooling is shaken in a box containing some plumbago, it breaks up at the instant of solidifying into a fine powder, which is about five times as heavy as sand. If after being sifted to select the grains of proper size, it is allowed to run through a small hole, the flow is seen to be entirely different from that of sand, looking as if a wire or solid rod were descending, and not an aggregation of particles. It is probable, therefore, that it would do better than sand for this purpose. I have not, however, given it a fair trial, because just at the time when the experiments with the sand-clock had reached this point, I determined to try a clepsydra as a prime mover.

The reason which led to this change was that it was observed on a certain occasion when the atmosphere was steady, that the photographs did not correspond in sharpness, being in fact no better than on other nights when there was a considerable flickering motion in the air. A further investigation showed that in these columns of sand there is apt to be a minute vibrating movement. At the plate-holder above this is converted into a series of arrests and advances. On some occasions, however, these slight deviations from continuous motion are entirely absent, and generally, indeed, they cannot be seen, if the parts of the image seem to vibrate on account of currents in the air. By the aid of the microscopic exaggeration described on a former page—which was subsequently put in practice—they may be observed easily, if present.

When the negative produced at the focus of the great mirror is intended to be enlarged to two feet or more in size, these movements injure it sensibly. A variety of expedients was resorted to in order to avoid them, but none proved on all occasions successful.

It is obvious that in a water-clock, where the mobility of the fluid is so much greater than that of solid grains, this difficulty would not arise. The following contrivance in which the fault of the ordinary clepsydra, in varying rate of flow as the column shortens, is avoided, was next made. With it the best results are attainable, and it seems to be practically perfect.

Fig. 35.



The Clepsydra.

It consists of a cylinder *a*, in which a piston *b* moves watertight. At the top of the piston rod is a leaden five-pound weight *c*, from which the cord *i* goes to the sliding plateholder *g*. The lower end of the cylinder terminates in a stopcock *d*, the handle of which carries a strong index rod *e*, moving on a divided arc. At *f* a tube with a stopcock is attached. Below, a vessel *h* receives the waste fluid.

In using the clepsydra the stopcock of *f* is opened, and the piston being pulled upwards, the cylinder fills with water from *h*. The stopcock is then closed, and if *d* also is shut, the weight will remain motionless. The string *i* is next connected with the slide, and the telescope turned on the moon. As soon as the slide is adjusted in angular position (page 36) the stopcock *d* is opened, until the weight *c* moves downwards, at a rate that matches the moon's apparent motion.

In order to facilitate the rating of the clepsydra, the index rod *e* is pressed by a spring *k* (2), against an excentric *l*. As the excentric is turned round, the stopcock *d* is of course opened, with great precision and delicacy. The plug of this stopcock (3) is not perforated by a round hole, but has a slit. This causes equal movements in the rod *e*, to produce equal changes in the flow. The rating requires consequently only a few moments.

The object of the side tube *f* is to avoid disturbing *d* when it becomes necessary to refill the cylinder, for when it is once opened to the right degree, it hardly requires to be touched again during a night's work. In order to arrest the downward motion of the piston at any point, a clamp screws on the piston rod, and can be brought into contact with the cylinder head, as in the figure.

That this instrument should operate in the best manner, it is essential to have the interior of the brass cylinder polished from end to end, and of uniform diameter. If any irregularity should be perceived in the rate of going, it can be cured completely by taking out the piston, impregnating its leather stuffing with fine rotten stone and oil, and then rubbing it up and down for five minutes in the cylinder, so as to restore the polish. The piston and cylinder must of course be wiped, and regreased with a mixture of beeswax and olive oil (equal parts) after such an operation. In replacing the piston, the cylinder must be first filled with water, to avoid the presence of air, which would act as a spring.

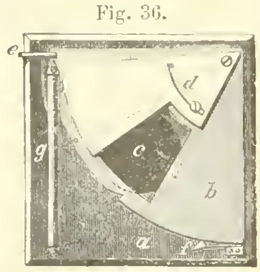
Although it may be objected that this contrivance seems to be very troublesome to use, yet that is not the case in practice. Even if it were, it so far surpasses any prime mover that I have seen, where the utmost accuracy is needed, that it would be well worth employing.

c. *The Sun Camera.*

In taking photographs of the sun with the full aperture of this telescope, no driving mechanism is necessary. On the contrary, the difficulty is rather to arrange the apparatus so that an exposure short enough may be given to the sensitive plate, and solarization of the picture avoided. It is not desirable to reduce the aperture, for then the separating power is lessened. The time required to obtain a negative is a very small fraction of a second, for the wavy appearance produced by atmospheric disturbance is not unfrequently observed sharply defined in the photograph, though these aerial motions are so rapid that they can scarcely be counted. Some kind of shutter that can admit and cut off the solar image with great quickness is therefore necessary.

In front of an ordinary camera *a*, Fig. 36, attached to the eyepiece holder of the telescope, and from which the lenses have been removed, a spring shutter is fixed.

Fig. 36.



The Spring Shutter.

It consists of a quadrant of thin wood *b*, fastened by its right angle to one corner of the camera. Over the hole in this quadrant a plate of tin *d* can be adjusted, and held in position by a screw moving in a slot so as to reduce the hole if desired to a mere slit. It may vary from $1\frac{1}{2}$ inch to less than $\frac{1}{50}$ of an inch. The quadrant is drawn downwards by an India-rubber spring *g*, 1 inch wide, $\frac{1}{8}$ of an inch thick, and 8 inches long. This spring is stretched when in action to about 12 inches, and when released draws the slit past the aperture *c* in the camera. Two nicks in the edge of the quadrant serve with the assistance of a pin *e*, which can easily be drawn out by a lever (not shown in the cut), to confine the slit either opposite to or above *e*. A catch at *f* prevents the shutter recoiling. The sensitive plate is put inside the box as usual in a plate-holder. When a photograph is taken, the spring shutter is drawn up so that the lower nick in the edge of the quadrant is entered by the pin *e*, and the inside of the camera obscured. The front slide of the plateholder is then removed in the usual manner, and the solar image being brought into proper position by the aid of the telescope finder, the trigger retaining *e* is touched, the shutter flies past *e*, and the sensitive plate may then be removed to be developed.

To avoid the very short exposure needed when a silvered mirror of 188 square inches of surface is used, I have taken many solar photographs with an unsilvered mirror, which only reflects according to Bouguer $2\frac{1}{2}$ per cent. of the light falling upon it, and should permit an exposure 37 times as long as the silvered mirror. This is the first time that a plain glass mirror has been used for such a purpose, although Sir John Herschel suggested it for observation many years ago. But eventually this application of the unsilvered mirror had to be abandoned. It has, it is true, the advantage of reducing the light and heat, but I found that the moment the glass was exposed to the Sun, it commenced to change in figure, and alter in focal length. This latter difficulty, which sometimes amounts to half an inch, renders it well nigh impossible to find the focal plane, and retain it while taking out the ground glass, and putting in the sensitive plate. If the glass were supported by a ring around the edge, and the back left more freely exposed to the air, the difficulty would be lessened but not avoided, for a glass mirror can be raised to 120° F. on a hot day by putting it in the sunshine, though only resting on a few points. Other means of reducing the light and heat, depending on the same principle, can however be used. By replacing the silvered diagonal mirror with a black glass or plain unsilvered surface, as suggested by Nasmyth, the trouble sensibly disappears.

I have in this way secured not only maculæ and their penumbræ, but also have obtained faculæ almost invisible to observation. On some occasions, too, the precipitate-like or minute flocculent appearance on the Sun's disk was perceptible.

It seems, however, that the best means of acquiring fine results with solar photography, would be to use the telescope as a Cassegranian, and produce an image so much enlarged, that the exposure would not have to be conducted with such rapidity. Magnifying the image by an eyepiece would in a general way have the same result, but in that case the photographic advantages of the reflector would be lost, and it would be no better than an achromatic.

§ 4. THE OBSERVATORY.

This section is divided into *a*, The Building; *b*, The Dome; and *c*, The Observer's Chair.

a. *The Building.*

The Observatory is on the top of a hill, 225 feet above low water mark, and is in Latitude 40° 59′ 25″ north, and Longitude 73° 52′ 25″ west from Greenwich, according to the determinations of the Coast Survey. It is near the village of Hastings-upon-Hudson, and is about 20 miles north of the city of New York. The surrounding country on the banks of the North River is occupied by country seats, on the slopes and summits of ridges of low hills, and no offensive manufactories

Fig. 37.

Dr. Draper's Observatory.

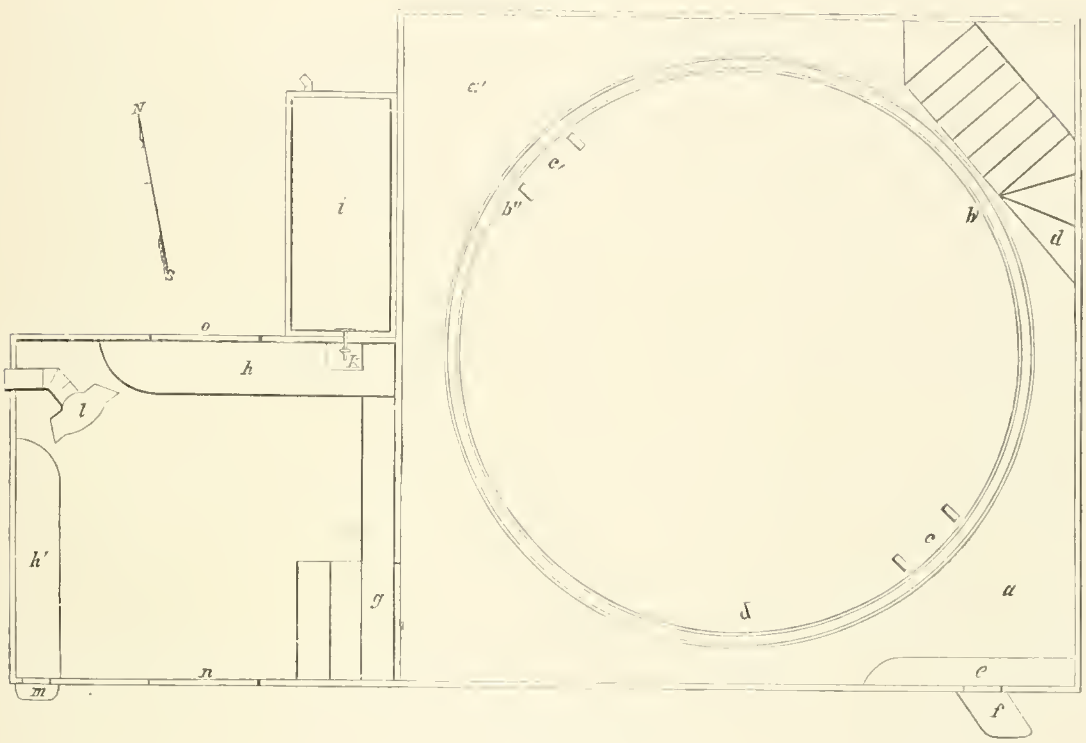
vitiate the atmosphere with smoke. Our grounds are sufficiently extensive to exclude the near passages of vehicles, and to avoid tremor and other annoyances.

An uninterrupted horizon is commanded in every direction, except where trees near the dwelling house cut off a few degrees toward the southwest. The advantages of the location are very great, and often when the valleys round are filled with foggy exhalations, there is a clear sky over the Observatory, the mist flowing down like a great stream, and losing itself in the chasm through which the Hudson here passes.

The foundation and lower story of the building are excavated out of the solid granite, which appears at the edge of the hill. This arrangement was intended to keep the lower story cool, and avoid, in the case of the metal reflector, sudden changes of temperature. The eastern side of the lower story, however, projects over the brow of the hill, and is therefore freely exposed to the air, furnishing, when desired, both access and thorough ventilation through the door. The second story or superstructure is of wood, lined inside with boards like the story below. They serve to inclose in both cases a non-conducting sheet of air.

The inside dimensions of both stories taken together are $17\frac{1}{2}$ feet square, and 22 feet high, to the apex of the dome. This space is unnecessarily large for the telescope, which only requires a cylinder 13 feet in diameter and 13 feet high. A general idea of the internal arrangement is gained from Fig. 28. In Fig. 38, *a a'* is the

Fig. 38.



Plan of Observatory (upper floor).

floor of the gallery, *b b' b''* the circular aperture in which the telescope *c c'* turns. The staircase is indicated by *d*. The Enlarger, § 6, rests on the shelf *e*, the heliostat being outside at *f*. The door going into the photographic room is at *g*, *h h'* are tables, *i* the water tank, *k* the tap and sink, *l* the stove, *m* a heliostat shelf, *n* the door, *o* the window.

The building is kept ventilated by opening the door in the lower part, and the dome shutter, seen in Fig. 37, for some time before using the instrument. On a summer day the upper parts, and especially those close under the dome, become without this precaution very hot, and this occurred even before the tin roof was painted. Bright tinplate seems not to be able to reflect by any means all the heat that falls upon it, but will become so warm in July that rosin will melt on it, and insects which have lighted in a few moments dry up, and soon become pulverizable. A knowledge of these facts led to the abandonment of wooden sheathing under the tin, for without it when night comes on the accumulated heat radiates away rapidly, and ceases to cause aerial currents near the telescope.

The interior of the building is painted and wainscoted, and the roof is ornamented partly in blue and oak, and partly with panels of tulip-tree wood.

There are only two windows, and they are near the southern angles of the roof. While they admit sunshine on some occasions, they can on others be closed, and the interior be reduced to darkness. In the southeast corner a small opening *e* may allow a solar beam three inches in diameter to come in from a heliostat outside. The greatest facilities are thus presented for optical and photographical experiments, for in the latter case the whole room can be used as a camera obscura.

b. *The Dome.*

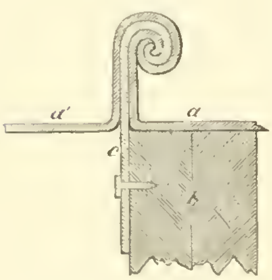
The roof of the observatory is 20 feet square. The angles are filled in solid, and a circular space 15 feet in diameter is left to be covered by the revolving dome. Although such a construction is architecturally weak and liable to lose its level, yet the great advantages of having the building below square, and the usefulness of the corners, determined its adoption, the disadvantages being overcome by a very light dome.

The dome is 16 feet in outside diameter, and rises to a height of 5 feet above its base. It is, therefore, much flatter than usual, in fact, might have been absolutely flat, with this method of mounting. It would then have been liable, however, to be crushed in by the deep winter snows.

It consists of 32 ribs, arcs of a circle, uniting at a common centre above. Each one is formed of two pieces of thin whitewood, *b*, Fig. 39, fastened side by side, with the best arrangements of the grain for strength. They are three inches wide and one inch thick at the lower end, and taper gradually to $2\frac{1}{2}$ by 1.

Over these ribs tinplate is laid in triangular strips or gores, about 18 inches wide at the base, and 10 feet long. Where the adjacent triangles of tin *a a′* meet, they are not soldered, but are bent together. This allows a certain amount of contraction and expansion, and is water-proof. It strengthens the roof so much, that if the ribs below were taken away, this corrugated though thin dome would probably sustain itself. The tin is fastened to the dome ribs *b* by extra pieces *c* inserted in the joint and doubled with the other parts, while below they are nailed to the ribs. In the figure the tin is represented very much thicker than it is in reality.

Fig. 39.



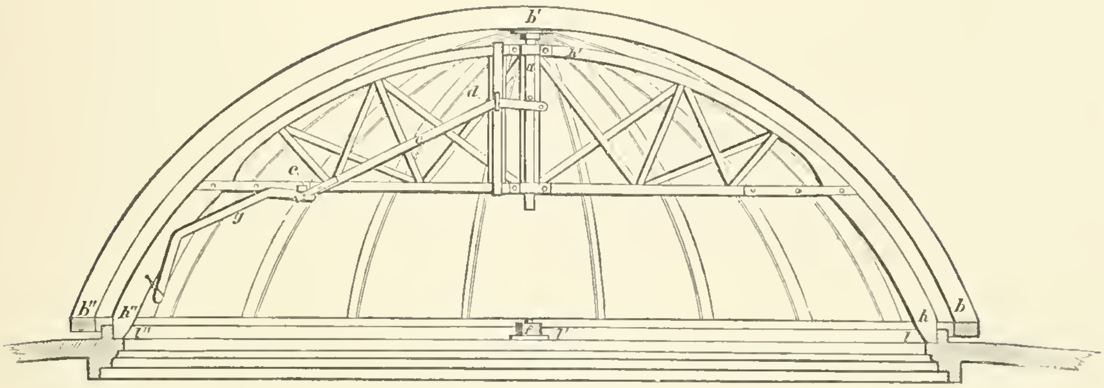
Joints in Tin of Dome.

This dome, although it has 250 square feet of surface, only weighs 250 pounds. That at the Cambridge (Massachusetts) Observatory, $29\frac{1}{2}$ feet in diameter, weighs 28,000 pounds.

The slit or opening is much shorter than usual, only extending half way from the base towards the summit. It is in reality an inclined window, $2\frac{1}{2}$ feet wide at the bottom, $1\frac{1}{2}$ wide at the top, and 4 feet long. It is closed by a single shutter, as seen in Fig. 37, and this when opened is sustained in position by an iron rod furnished with a hinge at one end and a hook at the other.

The principal peculiarity of the dome, the means by which it is rotated, remains to be described. Usually in such structures rollers or cannon balls are placed at intervals under the edge, and by means of rack work, a motion of revolution is slowly accomplished. Here, on the contrary, the whole dome *b b′ b″* (Fig. 40) is supported on an arch *h h′ h″*, carrying an axis *a* at its centre, around which a slight direct force, a pull with a single finger, will cause movement, and by a sudden push even a quarter of an entire revolution may be accomplished. It is desirable, however, to let it rest on the edge *b b''*, when not in use. At *e* there is an iron catch on the arch, by which the lever *c*, that raises the dome, is held down. The fulcrum

Fig. 40.



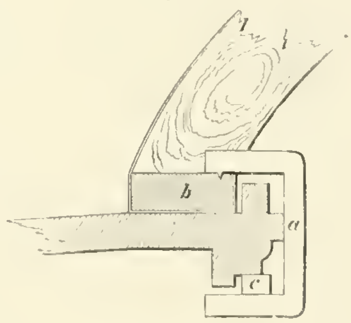
The Dome Arch.

is at *d*. The lever is hinged near *c*, so that when by being depressed it should have come in the way of the telescope below, the lower half *g* can be pushed up, the part from *c* toward *d* still holding the dome supported.

The arch can be set across the observatory in any direction, north and south, east and west, or at any intermediate position, because the abutments where the ends rest, are formed by a ring *l l' l''*, fastened round the circular aperture, through the stationary part of the roof.

When the telescope is not in use, and the dome is let down, so that there is no longer an interval of a quarter of an inch between it and the rest of the roof, it is confined inside by four clamps and wedges. Otherwise, owing to its lightness, it would be liable to be blown away. These clamps *a*, Fig. 41, are three sides of a square, made of iron one inch square. They catch above by a point in the wooden basis-circle of the dome *b*, and below are tightened by the wedge *c*.

Fig. 41.



A Dome Clamp.

When the dome is raised it is prevented from moving laterally and sliding off by three rollers, one of which is seen at *f*, Fig. 40. These catch against its inner edge, and only allow slight play. At first it was thought necessary to have a subsidiary half arch at right angles to the other to hold it up, but that is now removed.

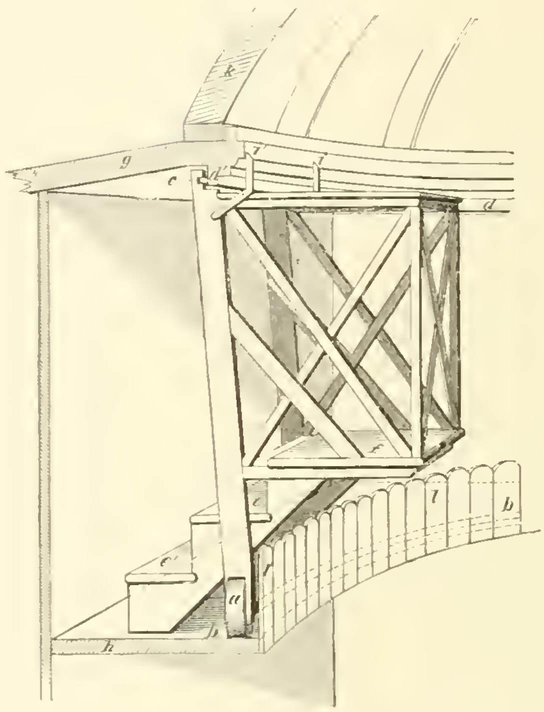
All the parts work very satisfactorily, and owing to the care taken to get the roof-circle and basis-circle flat and level, no leakage takes place at the joint, and even snow driven by high winds is unable to enter.

c. *The Observer's Chair.*

This is not a chair in the common acceptation of the word, but is rather a movable platform three feet square, capable of carrying two or more persons round the observatory, and maintaining them in an invariable position with regard to the telescope eyepiece.

Its general arrangement is better comprehended from the sketch, Fig. 42, than from a labored description. Below, it runs on a pair of wheels *a* (one only is

Fig. 42.



The Observer's Chair.

visible) 9 inches in diameter, whose axles point to the centre of the circle upon which they run. They are prevented from shifting outwards by a wooden railroad *b, b'*, and inwards by the paling *l, l'*. Above, the chair moves on a pair of small rollers *c*, which press against a circular strip or track *d, d'*, nailed around the lower edge of the dome opening. Access to the platform is gained by the steps *e, e'*. Attached to the railing of this platform, and near it on the telescope, are two tables (not shown in the figure) for eyepieces, the sliding plateholder, &c.

§ 5. THE PHOTOGRAPHIC LABORATORY.

This section is divided into *a*. Description of the Apartment; and *b*. Photographic Processes.

a. *Description of the Apartment.*

The room in which the photographical operations are carried on, adjoins and connects with the observatory on the southeast, as is shown in Figs. 28 and 38. It is 9 by 10 feet inside, and is supplied with shelves and tables running nearly all the way round, which have upon them the principal chemical reagents. It is furnished, too, with an opening to admit, from a heliostat outside, a solar beam of any size, up to three inches in diameter.

The supply of water is derived from rain falling on the roof of the building, and running into a tank *i*, Fig. 38, which will contain a ton weight. The roof exposes a surface of 532 square feet, and consequently a fall of rain equal to one inch in depth, completely fills the tank. During the course of the year the fall at this place is about 32 inches, so that there is always an abundance. In order to keep the water free from contamination, the roof is painted with a ground mineral compound, which hardens to a stony consistence, and resists atmospheric influences well. The tank is lined with lead, but having been in use for many years for other purposes, is thoroughly coated inside with various salts of lead, sulphates, &c. In addition the precaution is taken of emptying the tank by a large stopcock when a rainstorm is approaching, so that any accumulation of organic matter, which can reduce nitrate of silver, may be avoided. It has not been found feasible to use the well or spring water of the vicinity.

The tank is placed close under the eaves of the building, so as to gain as much head of water as is desirable. From near its bottom a pipe terminating in a stopcock *k*, Fig. 38, passes into the Laboratory. In the northeast corner of the room, and under the tap is a sink for refuse water and solutions, and over which the negatives are developed. It is on an average about twelve feet distant from the telescope. In another corner of the room is a stove, resembling in construction an open fireplace, but sufficient nevertheless to raise the temperature to 80° F. or higher, if necessary. As a provision against heat in summer, the walls and roof are double, and a free space with numerous openings above is left for circulation of air, drawn from the foundations. The roof is of tinplate, fastened directly to the rafters, without sheathing, in order that heat may not accumulate to such an extent during the day as to constitute a source of disturbance when looking across it at night.

For containing negatives, which from being unvarnished require particular care, there is at one side of the room a case with twenty shallow drawers each to hold eighteen. They accumulate very rapidly, and were it not for frequent reselections the case would soon be filled. On some nights as many as seventeen negatives have been taken, most of which were worthy of preservation. Not less than 1500 were made in 1862 and '63.

b. *Photographic Processes.*

In photographic manipulations I have had the advantage of my father's long continued experience. He worked for many years with bromide and chloride of silver in his photo-chemical researches (Journal of the Franklin Institute, 1837), and when Daguerre's beautiful process was published, was the first to apply it to the taking of portraits (Phil. Mag., June, 1840) in 1839; the most important of all the applications of the art. Subsequently he made photographs of the interference spectrum, and ascertained the existence of great groups of lines *M, N, O, P,* above *H,* and totally invisible to the naked eye (Phil. Mag., May, 1843). The importance of these results, and of the study of the structure of flames containing various elementary bodies, that he made at the same time, are only now exciting the interest they deserve.

In 1850, when his work on Physiology was in preparation, and the numerous illustrations had to be produced, I learnt microscopic photography, and soon after prepared the materials for the collodion process, then recently invented by Scott Archer. We produced in 1856 many photographs under a power of 700 diameters, by the means described in the next section.

At first the usual processes for portrait photography were applied to taking the Moon. But it was soon found necessary to abandon these and adopt others. When a collodion negative has to be enlarged—and this is always the case in lunar photography, where the original picture is taken at the focus of an object glass or mirror—imperfections invisible to the naked eye assume an importance which causes the rejection of many otherwise excellent pictures. Some of these imperfections are pinholes, coarseness of granulation in the reduced silver, liability to stains and markings, spots produced by dust.

These were all avoided by washing off the free nitrate of silver from the sensitive plate, before exposing it to the light, and again submitting it to the action of water, and dipping it back into the nitrate of silver bath before developing. The quantity of nitrate of silver necessary to development when pyrogallic acid is used, is however better procured by mixing a small quantity of a standard solution of that salt with the acid.

The operation of taking a lunar negative is as follows. The glass plates $2\frac{3}{4} \times 3\frac{1}{4}$ inches are kept in nitric acid and water until wanted. They are then washed under a tap, being well rubbed with the fingers, which have of course been properly cleaned. They are wiped with a towel kept for the purpose. Next a few drops of iodized collodion are poured on each side, and spread with a piece of cotton flannel. They are then polished with a large piece of this flannel, and deposited in a close dry plate box. This system of cleaning with collodion was suggested by Major Russel, to whose skilful experiments photography is indebted for the tannin process. It certainly is most effective, the drying pyroxyline removing every injurious impurity. There is never any trouble from dirty plates.

The stock of plates for the night's work, a dozen or so, being thus prepared, one of them is taken, and by movement through the air is freed from fibres of cotton. It is then coated with filtered collodion being held near the damp sink. The coated plate, when sufficiently dry, is immersed in a 40 grain nitrate of silver bath, acidified with nitric acid until it reddens litmus paper. The exact amount of acid in the bath makes in this "Washed Plate Process" but little difference. When the iodide and bromide of silver are thoroughly formed the plate is removed, drained for a moment, and then held under the tap till all greasiness, as it is called, disappears. Both front and back receive the current in turn.

It is then exposed, being carried on a little wooden stand, Fig. 43, covered with filtering paper to the telescope, and deposited on the sliding plateholder which has been set to the direction and rate of the moon, while the plate was in the bath. The time of exposure is ascertained by counting the beats of a half-second pendulum.

The method by which exposure without causing tremor is accomplished, is as follows: A yellow glass slides through the eyepiece-holder, Fig. 33, just in front of the sensitive plate, and is put in before the plate. The yellow-colored moon is centred on the collodion film, and the clepsydra and slide are set in motion, the mass of the telescope being at rest. A pasteboard screen is put in front of the telescope, and the yellow glass taken out. After 20 seconds the instrument remaining still untouched and motionless, the screen is withdrawn, and as many seconds allowed to elapse as desirable. The screen is then replaced and the plate taken back to the photographic room.

Fig. 43.

Plate Carrier.

After being again put under the tap to remove any dust or impurity, it is dipped into the nitrate bath for a few seconds. Two drachms of a solution of protosulphate of iron 20 grains, acetic acid 1 drachm, and water 1 ounce, is poured on it. As soon as the image is fairly visible this is washed off, and the development continued if necessary with a weak solution of pyrogallic acid and citro-nitrate of silver—pyrogallic and citric acids each $\frac{1}{5}$ grain, nitrate of silver $\frac{1}{10}$ grain, water 1 drachm. In order to measure these small quantities standard solutions of the substances are made, so that two drops of each contain the desired amount. They are kept in bottles, through the corks of which pipettes descend to just below the level of the liquid. This avoids all necessity of filtering, and yet no blemishes are produced by particles of floating matter.

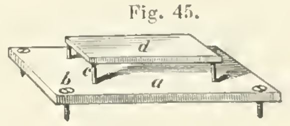
Fig. 44.

Pipette Bottle.

During the earlier part of the development, when the protosulphate of iron is on the film, an accurate judgment can be formed as to the proper length of time for the exposure in the telescope. If the image appears in 10 seconds, it will acquire an appropriate density for enlargement in 45 seconds, and will have the minimum of what is called fogging and the smallest granulations. If it takes longer to make its first appearance the exposure must be lengthened, and vice versa.

The latter part of the development, when re-development is practised, is purposely made slow, so that the gradation of tones may be varied by changing the proportion of the ingredients. As it would be tiresome and uncleanly to hold the plates in the hand, a simple stand is used to keep them level. It consists of a piece of thin wood *a*, Fig. 45, with an ordinary wood screw, as at *b*, going through each corner. Four wooden pegs, as at *c*, furnish a support for the plate *d*. By the aid of this contrivance and the washing system, I seldom get my fingers marked, and what is much more important, rarely stain a picture.

Fig. 45.



Developing Stand.

When the degree of intensity most suitable for subsequent enlargement is reached, that is, when the picture is like an overdone positive, the plate is again flooded with water, treated with cyanide of potassium or hyposulphite of soda, once more washed and set upon an angle on filtering paper to dry. It is next morning labelled, and put away unvarnished in the case.

To the remark that this process implies a great deal of extra trouble, it can only be replied that more negatives can be taken on each night than can be kept, and that, even were it not so, one good picture is worth more than any number of bad ones.

Although the above is the method at present adopted, and by which excellent results have been obtained, it may at any moment give place to some other, and is indeed being continually modified. The defects it presents are two—first, the time of exposure is too long, and second, there is a certain amount of lateral diffusion in the thickness of the film, and in consequence a degree of sharpness inferior to that of the image produced by the parabolic mirror. The shortest time in which the moon has been taken in this observatory has been one-third of a second, on the twenty-first day, but on that occasion the sky was singularly clear, and the intrinsic splendor of the light great. The full moon under the same circumstances would have required a much shorter exposure. A person, however, who has put his eye at the focus of such a silvered mirror will not be surprised at the shortness of the time needed for impressing the bromo-iodide film; the brilliancy is so great that it impairs vision, and for a long time the exposed eye fails to distinguish any moderately illuminated object. The light from 188 square inches of an almost total reflecting surface is condensed upon 2 square inches of sensitive plate.

Occasionally a condition of the sky, the reverse of that mentioned above, occurs. The moon assumes a pale yellow color, and will continue to be of that non-actinic tint for a month or six weeks. This phenomenon is not confined to special localities, but may extend over great tracts of country. In August, 1862, when our regiment was encamped in Virginia, at Harper's Ferry, the atmosphere was in this condition there, and was also similarly affected at the observatory, more than 200 miles distant. As to the cause, it was not forest or prairie fires, for none of them of sufficient magnitude and duration occurred, but was probably dust in a state of minute division. No continued rain fell for several weeks, and the clay of the Virginia roads was turned into a fine powder for a depth of many inches. The Upper Potomac river was so low that it could be crossed dry-shod. On a subsequent occasion when the same state of things occurred again, I exposed a series of plates (whose sensitiveness was not less than usual, as was proved by a standard artificial flame) to the image of the full moon in the $15\frac{1}{2}$ inch reflector for 20 seconds, and yet obtained only a moderately intense picture. This was 40 times as long as common.

Upon all photographic pictures of celestial objects the influence of the atmosphere is seen, being sometimes greater and sometimes less. To obtain the best impressions, just as steady a night is necessary as for critical observations. If the image of Jupiter is allowed to pass across a sensitive plate, a streak almost as wide as the planet is left. It is easily seen not to be continuous, as it would have been were there no atmospheric disturbances, but composed of a set of partially isolated images. Besides this planet, I have also taken impressions of Venus, Mars, double stars, &c.

An attempt has been made to overcome lateral diffusion in the thickness of the film by the use of dry collodion plates, more particularly those of Major Russel and Dr. Hill Norris. These present, it is true, a fine and very thin film during exposure, but while developing are so changed by wetting in their mechanical condition that no advantage has resulted. It was while trying them, that I ascertained the great control that hot water exercises over the rapidity of development, and time of exposure, owing partly no doubt to increase of permeability in the collodion film, but also partly to the fact that chemical decompositions go on more rapidly at higher temperatures. I have attempted in vain to develop a tannin plate when it and the solutions used were at 32° F., and this though it had had a hundred times the exposure to light that was demanded when the plate was kept at 140° F. by warm water.

Protochloride of palladium, which I introduced in 1859, is frequently employed when it is desired to increase the intensity of a negative without altering its thickness. This substance will augment the opacity 16 times, without any tendency to injure the image or produce markings. It is only at present kept out of general use by the scarcity of the metal.

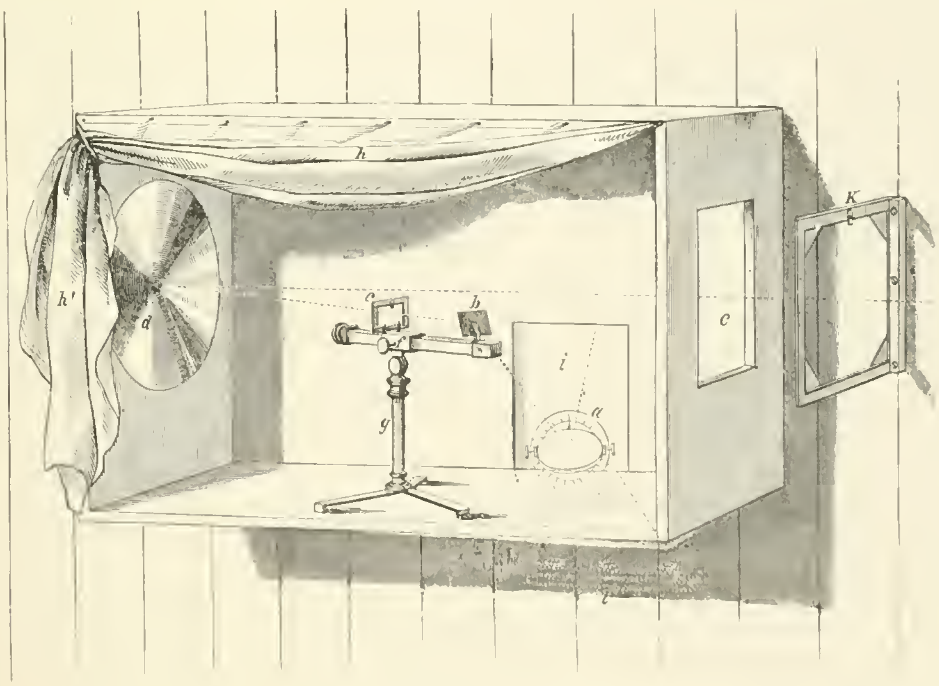
§ 6. THE PHOTOGRAPHIC ENLARGER.

Two distinct arrangements are used for enlarging, *a*, for Low Powers varying from 1 to 25; and *b*, for High Powers from 50 to 700 diameters.

a. *Low Powers.*

The essential feature in this contrivance is an entire novelty in photographic enlargement, and it is so superior to solar cameras, as they are called, that they are never used in the observatory now. It consists in employing instead of an achromatic combination of lenses, a *mirror* of appropriate curvature to magnify the original negatives or objects. The advantages are easily enumerated, perfect coincidence of visual and chemical foci, flat field, absolute sharpness of definition. If the negative is a fine one, the enlarged proofs will be as good as possible.

Fig. 46.



The Photographic Enlarger.

The mirror is of 9 inches aperture, and $11\frac{1}{2}$ inches focal length. It was polished on my machine to an elliptical figure of 8 feet distance between the conjugate foci, and was intended to magnify 7 times. At first the whole mirror was allowed to officiate, the object being illuminated by diffused daylight. But it was soon apparent, that although a minute object placed in one focus was perfectly reproduced at the other, seven times as large, yet a large one was not equally well defined in all its parts.

I determined then to produce the enlarged image by passing a solar-beam $1\frac{1}{2}$ inch in diameter through the original lunar negative—placed in the focus nearest to the mirror—and allowing it to fall on a portion of the concave mirror, $1\frac{1}{2}$ inch in diameter, at one side of the vertex. Being reflected, it returns past the negative, and goes to form the magnified image at the other focus of the ellipse.

In Fig. 46, *a* is the heliostat on a stone shelf outside; *b* a silvered glass mirror, to direct the parallel rays through *c*, the negative; *d* is the elliptical mirror; *e* an aperture to be partly closed by diaphragms; *f* a rackwork movement carried by the tripod *g*; the curtain *h h'* shuts out stray light from the interior of the observatory. The aperture *i* is also diaphragmed, but is shown open to indicate the position of the heliostat, the shelf of which joins the outside of the building at *l*. The dotted line points out the course of the light, which coming from the sun falls on the heliostat mirror *a*, then on *b*, through *c* to *d*, and thence returning through *e* to the sensitive plate in the plate holder *k*.

The distance of this last can be made to vary, being either two feet or twenty-eight feet from *d*. In the latter case a magnifying power of about 25 results, the moon being made three feet in diameter. The sensitive plate is carried by a frame, which screws to the side wall of the building, and can be easily changed in position. The focussing is accomplished by the rack *f*. Where so small a part ($1\frac{1}{2}$ inch) of the surface of the mirror is used, a rigid adherence then to the true foci of this ellipse is not demanded, the mirror seeming to perform equally well whether magnifying 7 or 25 times. Theoretically it would seem to be limited to the former power.

If instead of placing a lunar photograph, which in the nature of the case is never absolutely sharp, at *c*, some natural object, as for instance a section of bone, is attached to the frame moved by *f*, then under a power of 25 times it is as well defined as in any microscope, while at the same time the amount of its surface seen at once is much larger than in such instruments, and the field is flat. If the intention were, however, to make microscopic photographs, a mirror of much shorter focal length would be desirable, one approaching more to those of Amici's microscopes.

By the aid of a concave mirror used thus obliquely, or excentrically, all the difficulties in the way of enlarging disappear, and pictures of the greatest size can be produced in perfection. I should long ago have made lunar photographs of more than 3 feet in diameter, except for the difficulties of manipulating such large surfaces.

In order to secure a constant beam of sunlight a heliostat is placed outside the observatory, at its southeast corner *f*, Fig. 38. This beam, which can be sent for an entire day in the direction of the earth's axis, is intercepted as shown at *b*, Fig. 46, and thus if needed an exposure of many hours could be given. The interior of the observatory and photographic room being only illuminated by faint yellow rays, no camera box is required to cut off stray light. The eye is by these means kept in a most sensitive condition, and the focussing can be effected with the critical accuracy that the optical arrangement allows, no correction for chromatic aberration being demanded.

I have made all the parts of this apparatus so that they can be easily separated or changed. The flat mirrors are of silvered glass, and are used with the silvered side toward the light, to avoid the double image produced when reflection from both sides of a parallel plate of glass is permitted. The large concave mirror happens to be of speculum metal, but it can be repolished if necessary by means of a four inch polisher, passed in succession over every chord of the face. A yellow film of tarnish easily accumulates on metal specula if they are not carefully kept, and decreases their photographic power seriously.

Of the making of Reverses.— In addition to the use of the Enlarger for magnifying, it is found to have important advantages in copying by contact. The picture of the image of the moon produced in the telescope is negative, that is, the lights and shades are reversed. In enlarging such a negative reversal again takes place, and a positive results. This positive cannot, however, be used to make prints on paper, because in that operation reversing of light and shade once more occurs. It is necessary then at some stage to introduce still another reversal. This may be accomplished either by printing from the original negative a positive, which may be enlarged, or else printing from the enlarged positive a negative to make the paper proofs from. In either case a collodion film, properly sensitized, is placed behind the positive or negative, and the two exposed to light.

If diffused light or lamplight is used, the two plates must be as closely in contact as possible, or the sharpness of the resulting proof is greatly less than the original. This is because the light finds its way through in many various directions. If the two plates, however, are placed in the cone of sunlight coming from the Enlarger, and at a distance of fifteen or twenty feet from it, the light passes in straight lines and only in one direction through the front picture to the sensitive plate behind. I have not been able to see under these circumstances any perceptible diminution in sharpness, though the plates had been $\frac{1}{16}$ of an inch apart. It is perfectly feasible to use wet collodion instead of dry plates, no risk of scratching by contact is incurred, and the whole operation is easily and quickly performed. The time of exposure, 5 seconds, is of convenient length, but may be increased by putting a less reflecting surface or an unsilvered glass mirror in the heliostat. A diaphragm with an aperture of half an inch if placed at *e*, Fig. 46, to shut out needless light, and avoid injuring the sharpness of the reverse by diffusion through the room. In enlarging other diaphragms are also for the same reason put in the place of this one. For a half moon for instance, a yellow paper with a half circular aperture, whose size may be found by trial in a few minutes, is pinned against *e*.

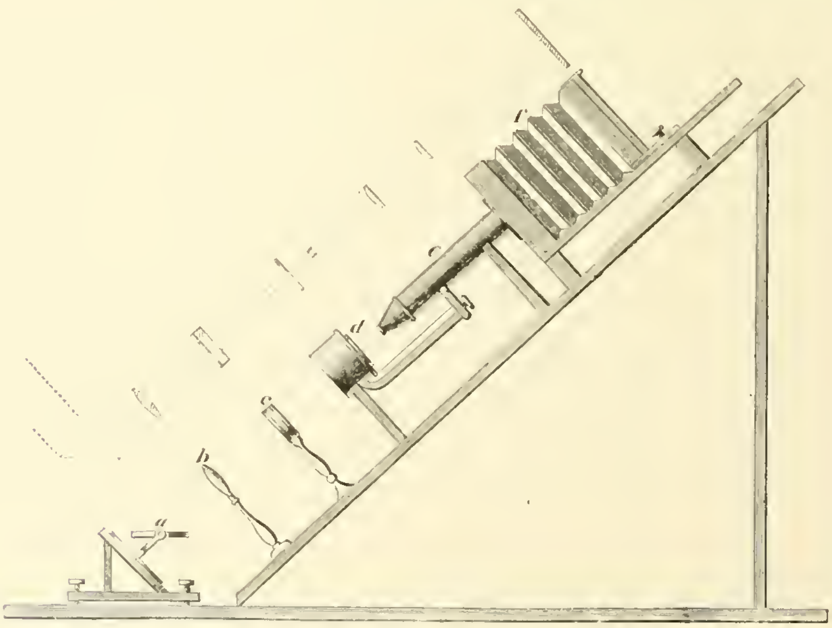
The enlarged pictures obtained by this apparatus are much better than can be obtained by any other method known at present. The effect, for instance, of a portrait, made life-size, is very striking. Some astronomers have supposed that advantages would arise from taking original lunar negatives of larger size in the telescope, that is, from enlarging the image two or three times by a suitable eye-piece or concave achromatic, before it reached the sensitive plate. But apart from the fact that a reflector would then have all the disadvantages of an achromatic, the atmospheric difficulties, which in reality constitute the great obstacle to success, would not be diminished by such means. The apparent advantage, that of not magnifying defects in the collodion, is not of much moment, for when development of the photographs is properly conducted, and thorough cleanliness practised, imperfections are not produced, and the size of the silver granules is not objectionable.

b. *High Powers.*

Although negatives of astronomical objects have not as yet been made which could stand the high powers of the arrangement about to be described, yet they bear the lower powers well, and give promise of improvement in the future.

Photography of microscopic objects as usually described, consists in passing a beam of light through the transparent object into the compound body of the microscope, and receiving it on its exit from the eyepiece upon a ground glass or sensitive plate. The difficulty which besets the instrument generally, and interferes with the production of fine results, arises from the uncertainty of ascertaining the focus or place for the sensitive plate. For if the collodion film be put where the image on ground glass seems best defined, the resulting photograph will not be sharp, because the actinic rays do not form their image there, but either farther from or nearer to the lenses, depending on the amount of the chromatic correction given by the optician. Practically by repeated trials and variation of the place of the sensitive compound, an approximation to the focus of the rays of maximum photographic intensity is reached.

Fig. 47.



Microscope for Photography.

During my father's experiments on light, and more particularly when engaged in the invention of portrait photography, he found that the ammonio-sulphate of copper, a deep blue liquid, will separate the more refrangible rays of light, the rays concerned in photography, from the rest. If a beam of sunlight be passed through such a solution, inclosed between parallel plates of glass, and then condensed upon an object on the stage of a microscope, a blue colored image will be formed on the ground glass, above the eyepiece. If the place of best definition be carefully ascertained, and a sensitive plate put in the stead of the ground glass, a sharp photograph will always result.

Besides, there is no danger of burning up the object, as there would be if the unabsorbed sunlight were condensed on it, and hence a much larger beam of light and much higher powers can be used. The best results are attained when an image of the sun produced by a short focussed lens is made to fall upon and coincide with the transparent object. In 1856 we obtained photographs of frog's blood disks, navicula angulata, and several other similar objects under a power of 700 diameters, excellently defined. Since then several hundreds of microscopic pictures have been taken.

In the figure, *a* is the heliostat, *b* a lens of three inches aperture, *c* the glass cell for the ammonio-sulphate of copper, *d* the object on the stage of the microscope *e*, *f* the camera for the ground glass or sensitive plate. Above the figure the course of the rays is shown by dotted lines.

In concluding this account of a Silvered Glass Telescope I may answer an inquiry which doubtless will be made by many of my readers, whether this kind of reflector can ever rival in size and efficiency such great metallic specula as those of Sir William Herschel, the Earl of Rosse, and Mr. Lassell? My experience in the matter, strengthened by the recent successful attempt of M. Foucault to figure such a surface more than thirty inches in diameter, assures me that not only can the four and six feet telescopes of those astronomers be equalled, but even excelled. It is merely an affair of expense and patience. I hope that the minute details I have given in this paper may lead some one to make the effort.

HASTINGS, WESTCHESTER COUNTY,
NEW YORK, 1863.

Postscript.—Since writing the above I have completed a photograph of the moon 50 inches in diameter. The original negative from which it has been made, bears this magnifying well, and the picture has a very imposing effect.

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ON THE MODERN REFLECTING TELESCOPE, AND THE MAKING AND TESTING OF OPTICAL MIRRORS

BY

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CENTRAL PART OF GREAT NEBULA IN ANDROMEDA. PHOTOGRAPHED BY G. W. RITCHEY, YERKES OBSERVATORY. TWO-FOOT REFLECTOR.

Enlarged 5.26 times
from original negative.

ON THE MODERN REFLECTING TELESCOPE, AND THE MAKING AND TESTING OF OPTICAL MIRRORS.

By G. W. Ritchey.

INTRODUCTION.

The present paper describes the methods employed by the writer in the optical laboratory of the Yerkes Observatory in making and testing spherical, plane, paraboloidal, and (convex) hyperboloidal mirrors. On account of the very great importance of supporting mirrors properly in their cells when in use in the telescope, a chapter is devoted to the description of an efficient support system for large mirrors. Intimately related to this, and equally important, is the subject of the mounting—the mechanical parts—of a modern reflecting telescope; accordingly, the final chapter is devoted to a consideration of this subject.

CHAPTER I.

DISKS OF GLASS FOR OPTICAL MIRRORS.

No greater mistake could be made than to assume that cheap and poorly annealed disks of glass, or those with large striæ or pouring marks, are good enough for mirrors of reflecting telescopes. While I am not prepared to say that optical glass of the finest quality must be used for mirrors in order to secure the best attainable results, it is evident that a very high degree of homogeneity and freedom from strain is necessary in order that the figure of mirrors shall not be injuriously affected by changes of temperature. If it were not necessary to consider the question of cost, I should advise the use of the finest optical (crown) glass always, in order to be as free as possible from risk; usually considerations of cost would, in the case of large mirrors, make it necessary to choose between such an optical disk of a given size and a somewhat larger one of the kind furnished by the St. Gobain

Company, for example. The diagonal plane mirror of a Newtonian, and the convex mirror of a Cassegrain reflector, should always be made of the best optical glass, since the expense for these is comparatively slight.

The writer has used many disks made at the celebrated glass-works of St. Gobain, near Paris, of sizes from 8 inches in diameter and 1½ inches thick, to the great one shown in the plates accompanying this article, which is 5 feet in diameter and 8 inches thick, and which weighs a ton. All of these disks are beautifully free from bubbles and large striæ, and are fairly well annealed, considering their great thickness. It is a most encouraging fact that the quality of the 5-foot disk is not inferior in any respect to that of disks of 8, 12, 20, 24, and 30 inches diameter which I have used. The makers of the 5-foot disk have recently expressed their readiness to undertake for us a 10-foot disk, one foot thick, which they think could now be made as perfect in all respects as the 5-foot disk. In ordering these disks it is always specified that great care be given to thorough stirring and thorough annealing. I have no doubt that in the case of very large and thick disks the makers could be prevailed upon to give even greater care to these points than is now given.

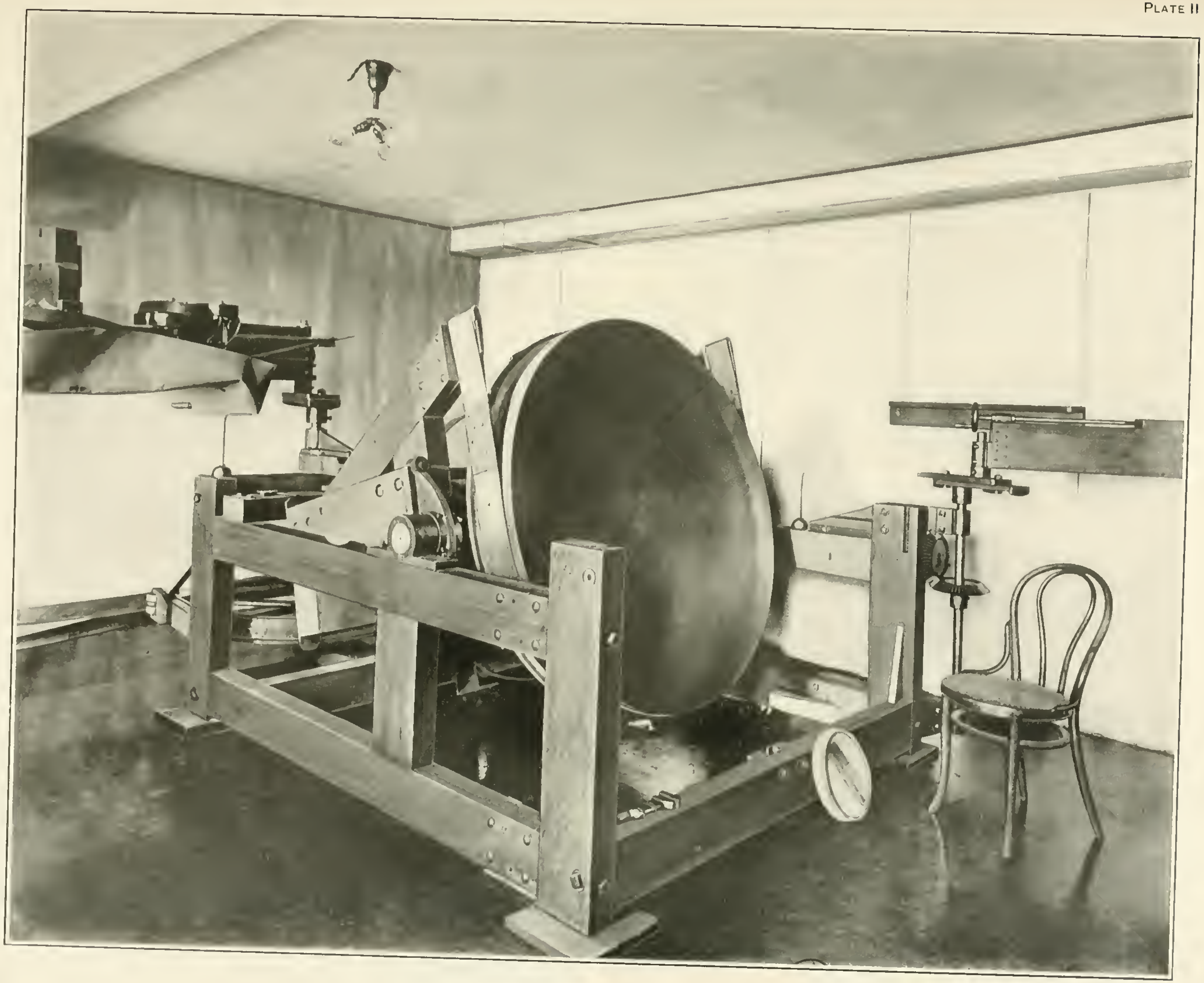
A very important point is in regard to the best thickness of optical mirrors. As a result of experience in making and using many mirrors of 24 and 30 inches diameter, in which the thickness of the several disks varies from one-twelfth to one-sixth of the diameter, I have no doubt that the thicker disks are always preferable, provided that they are as homogeneous and well-annealed as the thinner ones. The thinner mirrors suffer much greater temporary change of curvature from the very slight heat generated during the process of polishing; and they are undoubtedly more liable to suffer temporary disturbance of figure from changes of temperature when in use in the telescope. In the cases of the large paraboloidal mirror of a reflecting telescope, and the large plane mirror of a coelostat or heliostat, which should always be supported at the back to prevent flexure, the thickness should not be less than one-eighth or one-seventh of the diameter; in the writer's opinion the latter ratio leaves nothing to be desired. In the cases of the small diagonal plane mirror and the small convex mirror, which cannot easily be supported at the back, the thickness should be not less than one-sixth of the diameter.

All mirrors should be polished (not figured) and silvered on the back as well as on the face, in order that both sides shall be similarly affected by temperature changes when in use in the telescope; for the same reason the method of supporting the large mirror at the back, in its cell, should be such that the back is as fully exposed to the air as possible.

CHAPTER II.

THE OPTICAL LABORATORY OF THE YERKES OBSERVATORY.

A LARGE, well-lighted room, 70 feet long by 20 feet wide, in the north basement of the Observatory, was designed for the optical laboratory. The floor,



FIVE-FOOT MIRROR AND GRINDING MACHINE.
SHOWING METHOD OF TIPPING GLASS ON EDGE FOR TESTING.

which is nearly on a level with the ground outside, is of cement and is heavily painted. The walls are of brick, are about two feet thick, and are covered with two layers of heavy ceiling paper arranged so as to give two tight one-inch air-spaces for constant-temperature purposes. All joints of the paper are lapped and are nailed down with strips of wood. The ceiling of the room is heavily varnished.

The large room is divided into three rooms connected by large doors; these doors are so arranged that the entire length of the large room and of a wide hall opening from it, making an apartment 165 feet long, can be utilized for testing. The east and middle rooms of the three are used for grinding and polishing. The large windows of these rooms are fitted with storm sash on the inside; these are built in permanently and are made air-tight by means of ceiling paper. The west room contains the motor which supplies power to the grinding and polishing machines in the inner rooms; power is transmitted by a long shaft which runs the entire length of the rooms; this shaft is built in air-tight (to prevent dust) beneath the long work-bench which runs along one side of the rooms.

With these arrangements temperature, moisture, and freedom from dust can be controlled in the grinding and polishing rooms with all necessary refinement. In other respects, however, three great improvements could be made in planning an ideal optical shop; two of these relate to the comfort and health of the optician. First, the rooms should be arranged so that direct sunlight could be admitted to them during all parts of the optical work in which this would not be injurious to the work itself. Second, provision should be made for supplying to the rooms an abundance of fresh air, of a definite temperature, and washed free from dust. Third, for constant-temperature purposes, walls and partitions covered with a heavy layer of asbestos plaster (commercially termed Asbestic) would be preferable, on account of the superiority of the insulating and fire-proofing qualities of this material, to those of ceiling paper with air-spaces.

CHAPTER III.

GRINDING AND POLISHING MACHINES.

The grinding and polishing machines used by the writer are somewhat similar in principle to Dr. Draper's machine, shown in Fig. 25 of his book, but are more elaborate. I shall describe here the machine used in making the 5-foot mirror, both because it embodies most of the essential features of a grinding and polishing machine, and also because it is the only one of my machines of which I have a series of photographs for illustration. A good idea of this machine may be gained from the views of it shown in Plates II, III, IV, and VI.

The massive turntable upon which the glass rests consists of a vertical shaft or axis five inches in diameter, carrying at its upper end a very heavy triangular casting, upon which, in turn, is supported the circular plate upon which the glass lies. This plate is of cast-iron, weighs 1,800 pounds, is 61 inches in diameter, is heavily ribbed on its lower surface, and is connected to its supporting triangle by means of three large leveling screws. The surface of the large plate was turned and then ground approximately flat; two thicknesses of Brussels carpet are laid upon this, and the glass, with its lower surface previously ground flat, rests upon the innumerable springs formed by the looped threads of the carpet. No better support for a glass during grinding and polishing could be desired.

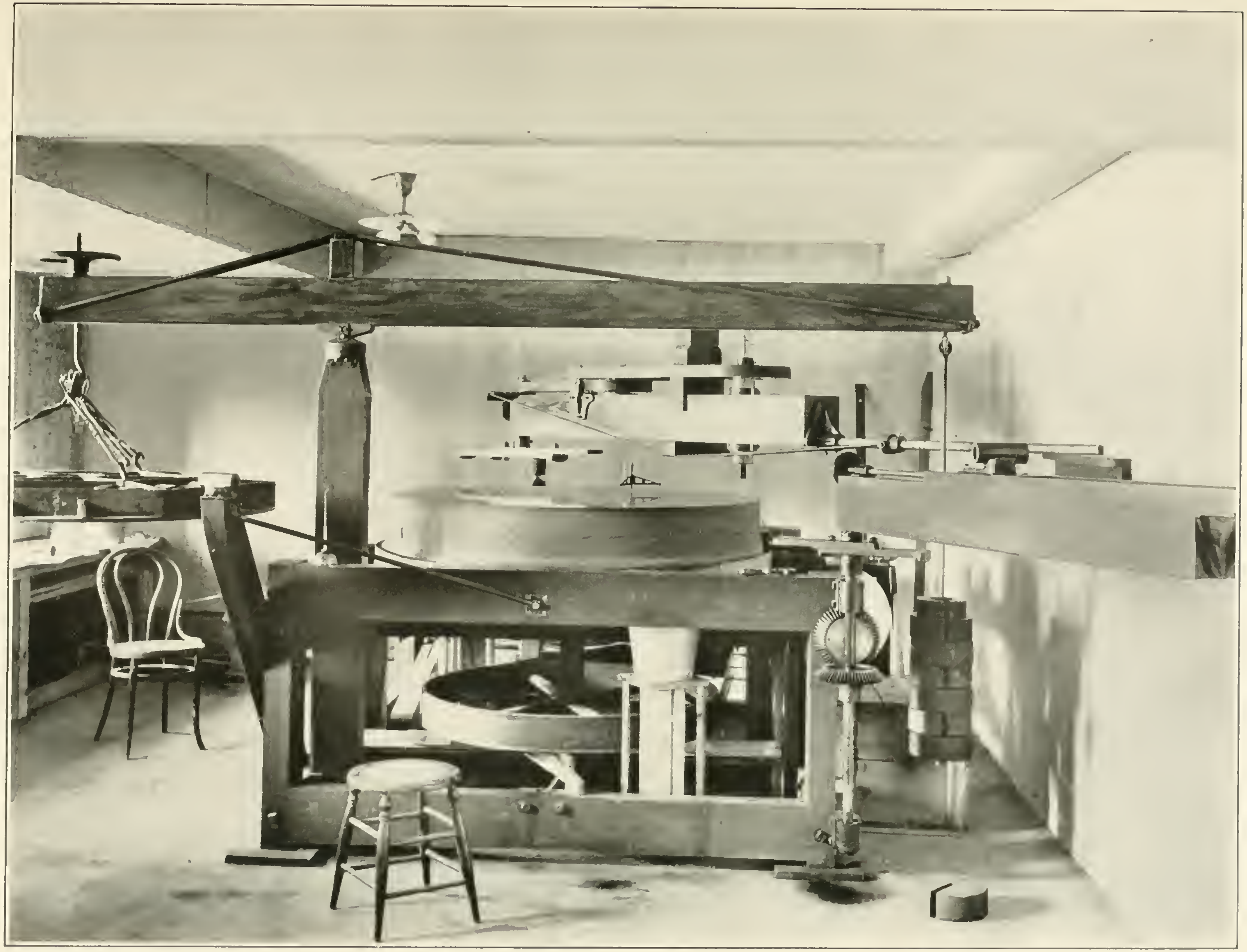
Three adjustable iron arcs at the edge of the glass serve for centering the latter upon the turntable, and prevent it from slipping laterally.

The entire turntable, with the heavy frame of wood and metal which supports it, can be turned through 90° about a horizontal axis, thus enabling the optician to turn the glass quickly from the horizontal position which it occupies during grinding and polishing, to a vertical position for testing. This is shown in Plate II.

The turntable is slowly rotated on its vertical axis by means of the large pulley below (Plate III). This rotation is effected by means of belting from the main vertical crank-shaft on the east end of the machine; this shaft is well shown at the left in Plate IV. At the upper end of this shaft is the large crank, with adjustable throw or stroke, which moves the large and strong main arm to which the grinding and polishing tools are connected, and by means of which they are moved about upon the glass. This I shall always refer to as the main arm. It is a square tube of oak wood, and is strong enough to carry the counterpoising lever shown in Plate IV, and the weight of any of the grinding tools, when fully or partially counterpoised. This main arm also carries the system of pulleys and belts by which the slow rotation of the grinding and polishing tools is rigorously controlled; these, and the manner in which this rotation is effected, are well shown in Plate IV.

The west end of the main arm consists of a strong steel shaft which slides in a massive bronze swivel-bearing which corresponds to the "elliptical hole in the oak block *p*" of Dr. Draper's machine (see his Fig. 25). But this bearing is not stationary as in Draper's machine; it is not only mounted on a long slide (which I shall refer to throughout this article as the transverse slide), so that it can be slowly moved for several feet across the west end of the machine by means of a long screw, but this bearing and slide are carried upon a secondary strong arm, which is moved by a secondary crank at the southwest corner of the machine. Unfortunately there is no photograph which shows this part of the machine as it appears when in use; Plates II and III show the secondary crank well, but the secondary arm is shown swung around with one end resting on a bracket on the wall, in order to have it out of the way.

The arrangement of the west end of the machine is the result of experience with several machines, and is found extremely serviceable and convenient. The long transverse slide on the secondary arm allows the grinding and polishing tools to be placed so as to act on any desired zone of the glass, from the center to the edge; and this setting can be changed as desired while the machine is running. The secondary crank, which turns at the same speed as the large one which drives the main arm, enables the optician to change as desired the width of the (approximately) elliptical stroke or path of the tool with reference to the length of this



FIVE-FOOT MIRROR AND GRINDING MACHINE.
SHOWING LEVER FOR HANDLING HEAVY GRINDING AND POLISHING TOOLS.

stroke; this change is especially desirable when figuring the glass; it is, of course, impossible when only one driving-crank is used.

I regard the transverse slide, or something equivalent to it, as absolutely necessary to the success of a grinding and polishing machine; it will be noticed that its purpose corresponds, in some measure, to that of the long slot in the main arm of Draper's machine; I have used both arrangements and have found the transverse slide to be far more effective and convenient in use; its use will be described in the chapters on grinding and polishing.

The secondary crank, while very desirable and convenient, for the reason given above, is not indispensable; I have used several smaller machines which have given good results without it.

The manner in which the grinding and polishing tools are connected to the main arm is shown in Plate IV. A vertical shaft, $1\frac{3}{8}$ inches in diameter and 24 inches long, both rotates and slides (vertically) freely in bronze bearings attached to the main arm. The grinding and polishing tools are connected to the lower end of this shaft through the medium of a large universal coupling,—a gimball or Hooke's joint,—with two pairs of horizontal pivots at right angles to each other; this allows the tools to rock freely in all directions in order to follow the curvature of the glass. The tools are lifted, for counterpoising them, by the lever above (see Plate IV), through the medium of the vertical shaft and the universal coupling. In the case of very massive grinding tools of moderate size, like that shown in this illustration, the universal coupling is connected directly to the back of the tool; but in the case of all large tools which are to be used for fine work this connection is made through the medium of a system of bars and triangles, so that the tools are counterpoised without the slightest danger of changing their shape. A small coupling with ball bearings at the upper end of the vertical shaft allows the latter to rotate freely with reference to the link which connects it to the counterpoise lever.

To recapitulate briefly: this method of connecting the grinding and polishing tools allows them to be controlled in all of the following ways simultaneously: (1) the stroke of the tool is given by the motion of the main arm; (2) the slow rotation of the tool is rigorously controlled by the belting above; (3) the tool is allowed to rock or tip freely by means of the universal coupling, in order that it may follow the curvature of the glass; (4) the tool rises and falls freely by means of the sliding of the $1\frac{3}{8}$-inch vertical shaft in its bearings, in order that it may follow the curvature of the glass; (5) the tool is counterpoised by means of the lever on the main arm, through the medium of the same vertical shaft and universal coupling.

In Plate III is shown the large lever by which the 5-foot glass, which weighs a ton, is lifted on and off the machine, and by means of which, also, the large grinding tools are handled. One of the full-size grinding tools, weighing 1,000 pounds, is shown suspended by the lever. The arrangements are so convenient that the optician alone can do all parts of the work.

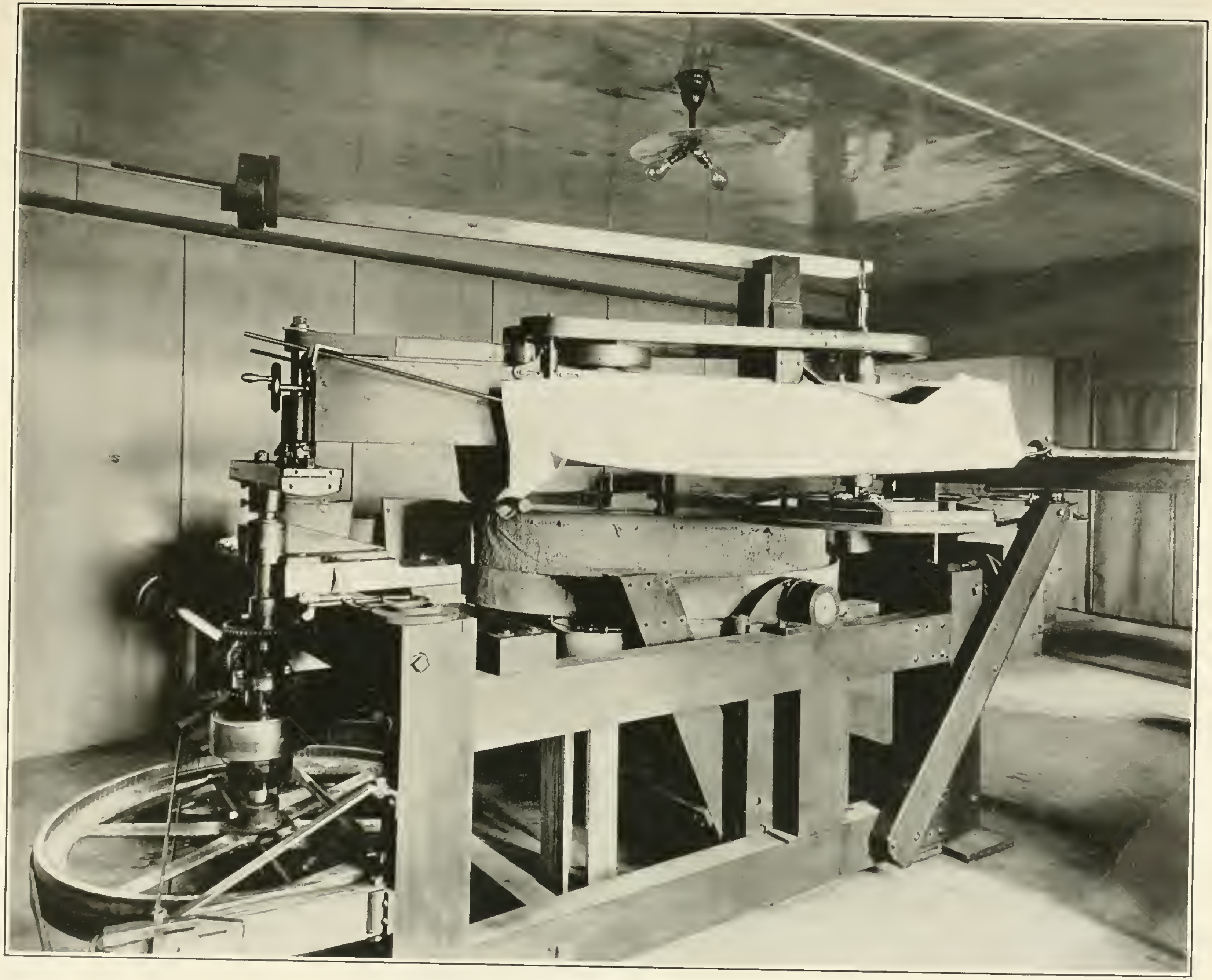
CHAPTER IV.

GRINDING TOOLS.

While grinding tools of glass were used in much of my earlier work, and are still used for small work, I now use cast-iron grinding tools for all large work. These are cast very heavy, with ribs on the back; the ribs are made heavy, but not deep (or high). For large work iron tools are cheaper than glass ones; they are more easily prepared; they are more easily and safely counterpoised, which is always necessary in the fine-grinding of large work; and they produce on the glass a fine-ground surface fully as smooth and perfect as can be obtained with glass tools.

An important question is in regard to the size of grinding tools,—whether they should be of the same diameter as the mirror. For mirrors up to 24 or 30 inches in diameter full-size tools are generally used. For concave mirrors larger than 30 inches in diameter I use grinding tools whose diameter is slightly more than half that of the glass, *i. e.*, a 16-inch tool for a 30-inch glass; a 32-inch tool for a 60-inch glass. These I shall refer to as half-size tools. Full-size tools are, of course, much more expensive and difficult to make; they are many times heavier than half-size tools of equal stiffness; and they require a much stronger grinding machine to counterpoise them properly; grinding can be done with them, however, more quickly than with the smaller tools. Half-size tools are economical and are quickly prepared; they are easily counterpoised; and a much greater variety of stroke can be used with them, so that with a well-designed grinding machine I have found it easier to produce fine-ground surfaces, entirely free from zones, with half-size than with full-size tools. If temperature conditions and uniform rotation of the glass are carefully attended to, the surface of revolution produced by the smaller tools is fully as perfect as that given by the larger ones; I always take the precaution, however, to work a full-size approximately flat tool on the glass before beginning to excavate the concave, so as to start out with a surface of revolution.

Grinding tools for concave and convex mirrors are always made in pairs, one concave, the other convex. Grinding tools for plane mirrors are made in triplicate. These iron tools, when being cast, are "poured" face down, so that the faces will be clean. I shall describe the preparation of a pair of iron tools for a concave mirror, leaving the description of tools for plane mirrors until the making of plane mirrors is discussed. The convex and concave tools are turned in a lathe to the proper curvature as shown by templets. The convex tool, which is, of course, to be used on the concave glass, is now placed on a planing machine, and has a series of grooves cut across the convex surface. These grooves are usually $\frac{1}{4}$ inch wide, and run in two directions at right angles to each other; these divide the surface into squares, which are usually made about one inch on a side. These grooves serve to distribute the grinding material uniformly, and entirely obviate the tendency of the tools to cling to the glass in fine-grinding. No grooves are cut in the concave tool. A number of holes are now bored through both tools, in such positions that wooden cups or funnels can be inserted into the holes from the back or ribbed side



FIVE-FOOT MIRROR AND GRINDING MACHINE.
SHOWING HALF-SIZE GRINDING TOOL SUSPENDED ON MAIN ARM.

of the tool, without interfering with the ribs; these cups serve for the introduction of the grinding material during the process of grinding; they should be thoroughly varnished.

The convex and concave tools are now ground together on the machine, with fine grades of carborundum (which is much more effective for this purpose than emery) and water. This eliminates the circular marks left by the lathe, and enables the optician to secure the exact curvature desired. A very important point is that by grinding with the concave tool on top, the radii of curvature of both tools can be gradually shortened; when the convex tool is used on top the curvature of both is gradually flattened. By this means, and the use of very fine grades of carborundum, a most perfect control of the curvature of the tools may be had.

The curvature of the tools and of the glass is measured by means of a large spherometer; this is shown in Plate v, resting upon a 12-inch glass grinding tool. The spherometer is of the usual three-leg form; the legs terminate in knife-edges, the lines of which are parts of the circumference of a 10-inch circle. The central screw is very carefully made; it was ground in its long nut (which was made adjustable for tightness) with very fine grades of emery such as are used in optical work; screw and nut were then smoothed and polished by working them together with rouge and oil. The screw is of $\frac{1}{2}$ millimeter pitch, and the head, which is 4 inches in diameter, is graduated to 400 divisions. On fine-ground surfaces settings can be made to one-half or one-third of a division, corresponding to a depth of $\frac{1}{40000}$ or $\frac{1}{60000}$ of an inch, approximately.

CHAPTER V.

POLISHING TOOLS.

After experience with polishing tools of various kinds, the tools which I now use exclusively for large work consist of a wooden disk or basis constructed in a peculiar manner, and covered on one side with squares of rosin faced with a thin layer of beeswax. The wooden disk may be replaced, in the case of small polishing tools up to 12 or 15 inches diameter, by a ribbed cast-iron plate so designed as to be extremely light and rigid; the bases of larger tools may be made of cast aluminum, but this, in order to be strong and rigid, must contain 15 % or more of other metals; such a basis for a 30-inch polishing tool weighs about sixty pounds, and the rough casting alone costs about fifty dollars. It is possible that a metal basis possesses an advantage over a wooden one in that its surface is less yielding. Tools properly constructed of wood, however, are light and extremely rigid, are easily made, and are economical in cost. As their proper construction is a matter of the utmost importance, I shall describe, somewhat in detail, the method of making wooden bases of from 15 to 40 inches diameter.

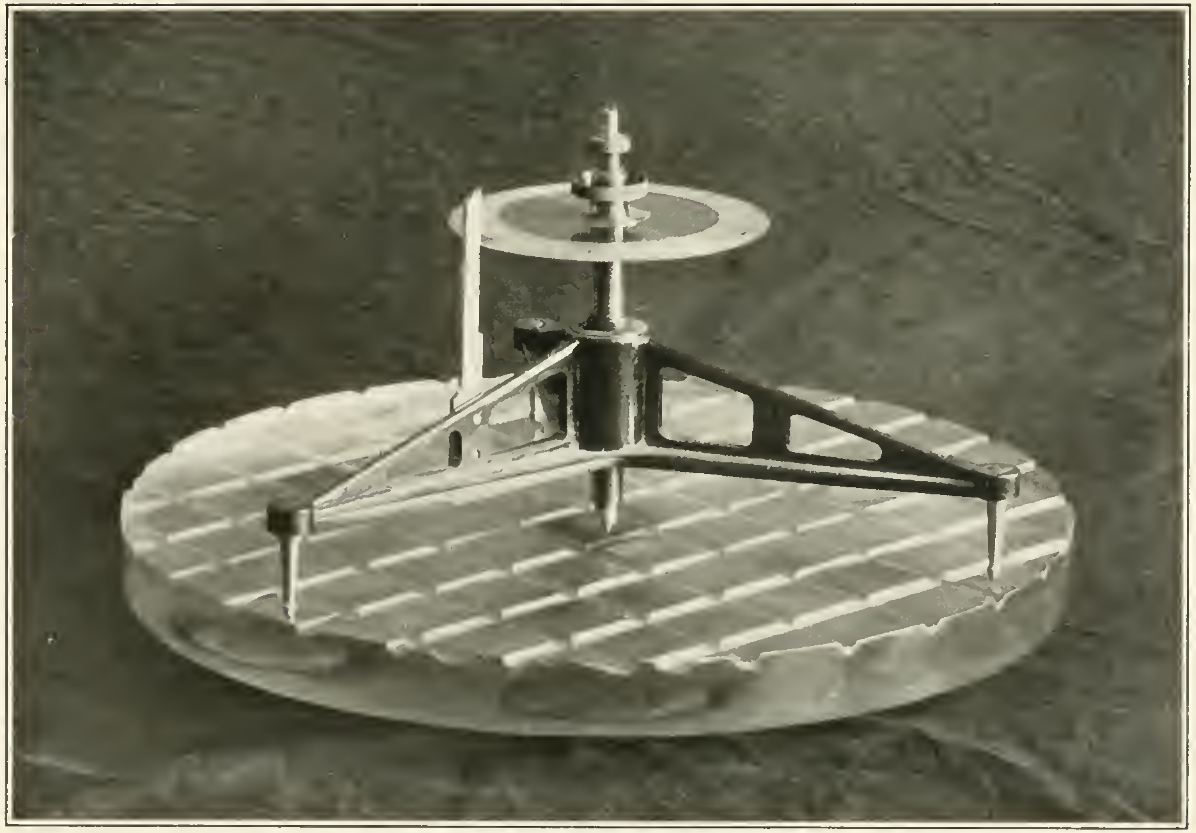
A large number of strips of dry and straight-grained pine wood $1\frac{1}{4}$ inches wide and $\frac{5}{16}$ inch thick are prepared; the wooden basis is built up of successive layers of these strips. The strips in all layers except the two outer ones are laid just $\frac{1}{4}$ of an inch apart. Those of each layer are placed at right angles to those of the next layer below, and are glued and nailed down with long wire brads. The best cabinet-maker's glue is used, and the strips are warmed before the glue is applied. Each crossing of the strips in the successive layers (*i. e.*, each of the $1\frac{1}{4}$-inch squares), is nailed with at least two nails. The upper surface of each layer is carefully planed flat before the next layer of strips is applied. For a 20-inch tool six layers of pine strips (each $\frac{5}{16}$ inch thick) are used; for a 24-inch tool, seven layers; for a 36-inch tool, ten layers. Next, one layer of thoroughly seasoned strips of hard straight-grained cherry wood about $\frac{3}{8}$ inch thick and slightly less than $1\frac{1}{2}$ inches wide is added, to form the outer layer at the back of the tool; these strips are laid almost touching each other. In the case of tools for flat mirrors, a precisely similar layer of cherry strips is added to form the outer layer at the front or face of the tool. But in the case of tools for concave or convex mirrors the strips composing the front layer must be made thicker, to allow for the curvature of the face of the tool. If this curvature is great, the cherry strips forming the front layer are made of double width (*i. e.*, slightly less than 3 inches wide), in order that the width of their bases shall be greater as compared with their thickness; this is usually done when the depth of the curve is greater than $\frac{1}{4}$ inch. The gluing and nailing of the outer layers of strips are done with the greatest thoroughness, four of the long fine nails being driven through into each of the squares of pine wood beneath. For tools less than 20 inches in diameter thinner strips and a larger number of layers are used. The entire thickness of the wooden disk or basis built up in this way should be between one-tenth and one-eighth of its diameter.

This wooden basis is next placed in a large lathe, the edge is turned smooth and to the proper diameter, and the face is turned to fit the curvature of the glass to be polished.

A round pan of galvanized iron large enough to contain the wooden disk having been prepared, enough hard paraffin is melted in it so that the disk can be soaked in the liquid paraffin; the latter must not be hotter than 150° Fahrenheit, otherwise the strength of the glue-joints will be injured. It is best to melt the paraffin on a gas or gasoline stove, so that the degree of heat can be easily controlled. The tool should soak for several hours, being moved continually and turned over often. Since the construction of the wooden basis is such that a great number of openings extend entirely through it, the melted paraffin permeates the entire tool thoroughly. The wooden tool prepared in this way is lighter than any metal tool of the same degree of stiffness, and is entirely impervious to the moisture which is necessary in the polishing room. The question of lightness is a most important one, as will be seen when the work of polishing is described later.

The front or face of the wooden basis is now lightly scraped with a wide, sharp chisel, to remove any excess of paraffin, and is then marked off for $1\frac{1}{4}$-inch squares of rosin, with grooves $\frac{1}{4}$ inch wide between them; the grooves should come exactly above the $\frac{1}{4}$-inch spaces left between the pine strips beneath.

The preparation of the rosin squares is usually a very troublesome matter, but



LARGE SPHEROMETER ON TWELVE-INCH GLASS GRINDING TOOL.

becomes easy when the following directions are observed. A clean, flat board, having an area about twice that of the polishing tool, is prepared. One face of this is covered with clean paper. Long strips of wood $\frac{1}{4}$ inch square are fastened upon the paper by means of fine brads; these strips are placed just $1\frac{1}{4}$ inches apart, and the ends of the grooves thus formed (grooves $1\frac{1}{4}$ inches wide, $\frac{1}{4}$ inch deep, and of any convenient length) are closed with strips of wood. The board is now carefully leveled. The rosin, when melted and softened to the proper degree, is to be poured into these grooves, which serve as moulds.

A quantity of rosin sufficient to fill all of the grooves is melted in a clean pan. Even when only a small quantity is needed it is best to melt at least ten pounds of rosin, since the entire process of "tempering" and pouring is more easily and satisfactorily carried on with large quantities than with small. Only lumps of clear, clean rosin should be used. A gas or gasoline stove is very convenient for melting the rosin, since the degree of heat can be easily controlled. When the rosin is melted the pan is removed from the stove and a quantity of turpentine, equal in weight to about $\frac{1}{25}$ of the rosin used, is added, and the mass thoroughly stirred. A tablespoonful of the liquid is now dipped out and immersed for several minutes in a bucket of water at the temperature of the polishing room, which should be about 68° Fahrenheit. The spoonful of rosin is now taken out, and its hardness tried with the thumb-nail. If the rosin is brittle at the thin edges it is still too hard, and a little more turpentine must be added; if, however, it is soft like wax or gum, it is too soft, in which case the pan of rosin must be hardened by boiling for a few minutes; this drives off the excess of turpentine. When the rosin is of the proper hardness an indentation about $\frac{1}{4}$ inch long can be made in it by moderate pressure of the thumb-nail for five seconds. When the proper degree of hardness has been obtained it is often necessary to heat the pan of rosin again so that it will not be too thick to pass readily through the strainer; this is a long, narrow bag of cheese-cloth through which the rosin is strained as it is being poured into the grooves or moulds previously described. If such heating is necessary it must be done gently and without boiling; otherwise the rosin will be hardened. Enough is poured into each groove to just fill it.

After being poured, the rosin should cool for six or eight hours. Then the nails which held the quarter-inch strips of wood to the board below are removed, and the layer of rosin, wooden strips, and paper is carefully lifted from the board, when the paper is easily stripped from the rosin, to which it does not adhere closely. With care the thin strips of wood can now be removed, one after the other, and the long strips of rosin, $1\frac{1}{4}$ inches wide and $\frac{1}{4}$ inch thick, are secured without chipping or breaking. These are now readily cut into squares with a hot knife.

The squares are attached to the previously marked wooden basis by quickly warming one face of each square over a flame and then pressing it gently against the tool with the fingers. The tool is now ready for rough-pressing.

Three strong eyes are screwed into the back of the tool, and it is suspended, face down (by means of wires connected to the ceiling of the room), so as to hang about two feet above the flame of a gas or gasoline stove. The tool can now be swung about so that the rosin squares are warmed uniformly. When the squares are slightly soft and very slightly warm, *but not hot*, to the touch, the tool is placed upon the previously ground glass which is to be polished, the glass having just previously been thoroughly wet with distilled water so that the rosin will not stick to it. Slight pressure may be exerted to assist in pressing the rosin surface to fit the glass. The tool will have to be slightly warmed and pressed several times before good contact is secured all over. I always prefer to "rough-press" the rosin tools on an iron grinding tool having the same form as the glass, if a sufficiently large one is available; but the precaution is always taken to cover the iron tool with clean wet paper.

The rosin squares will have spread somewhat irregularly during the rough-pressing; so the surface is marked with a straight-edge and knife, and the edges of the squares are trimmed so that the grooves between them are straight and of uniform width. This trimming is best done with a sharp knife, held so as to make an angle of about 60° with the surface of the tool, and drawn quickly toward the workman.

The rosin squares are now ready for coating with wax. A pound of best beeswax is melted in a large clean cup and is very carefully strained through several thicknesses of cheese-cloth into a similar clean cup. A brush is made by tying several thicknesses of cheese-cloth around the end of a thin blade of wood $1\frac{1}{4}$ inches wide. Each rosin square is now coated with a thin layer of wax, by a single stroke of the brush; the wax should be very hot, otherwise the layer will be too thick.

The tool is now ready for "cold-pressing" or "fine-pressing," a matter of the most vital importance, which will be more properly described later, in connection with the work of polishing the glass.

The work of making a large concave mirror will now be described in detail.

CHAPTER VI.

ROUGH-GRINDING THE FACE AND BACK OF A ROUGH DISK OF GLASS, AND MAKING THE SAME PARALLEL.

The rough disk of glass is placed upon the carpeted turntable, and a long strip of thin oilcloth is drawn around its edge; the upper edge of the oilcloth is securely fastened to the glass by means of a strong cord, and the junction between oilcloth and glass is made water-tight by means of water-proof adhesive tape. The oilcloth strip is wide enough to hang several inches below the edge of the iron plate on which the glass rests, so that the circular trough of galvanized iron, which can be seen in Plates IV and VI, catches all of the emery and water which are washed over the edges of the glass during grinding; this circular trough is stationary, has two holes in its bottom above the buckets, which can be seen in the plates, and is kept scraped clean by two scrapers which reach down into it from the revolving turntable. Several important results are thus secured: the carpet cushion under the glass is kept dry; the entire machine is kept perfectly free from the dripping of the grinding material; and all of the latter material is caught in buckets and is used again and again in the later and finer grinding.

The large irregularities of surface of large rough disks are usually ground away with coarse emery and a heavy, flat, half-size iron tool without grooves, the surface of which is rounded up considerably at the edge, so that the tool may rise easily over obstructing irregularities without breaking them. The grinding machine is set so that the half-size tool moves over the glass well out to one side of the latter; the rotation of the turntable of course brings all parts of the glass in succession under the tool; if the setting of the machine is such that the half-size tool passes in much beyond the center of the glass at every stroke, the surface of the latter will become concave.

When the marked irregularities of surface are ground away, the full-size, flat, grooved iron tool is put on. A tool of this kind is almost indispensable in making a mirror. Emery and water are supplied through the cups at the back of the tool, and the glass is quickly ground approximately flat. The glass is now turned over, and the other side is ground in a precisely similar manner.

The thickness of the glass is now tried, all around, by means of calipers. The approximately flat surfaces will probably be found to be far from parallel. If this is the case, the thick side may be ground down as follows: The belt which drives the turntable is loosened, until it will just rotate the latter, and a brake is arranged so that the workman can stop the rotation of the turntable at any desired point by pressing on the brake with his foot. A flat, half-size grooved tool is put on, and set so as to work far out to one side of the glass. A medium grade of emery (No. 70) is used, and the machine started. As the thick side of the glass, which has been marked, comes beneath the moving tool, the turntable is slowed down or stopped, so that a great excess of grinding is done on the thick side at each revolution. By distributing the grinding carefully, and trying the thickness often with the calipers, the upper surface is easily made parallel to the lower one. When this is done the full-size tool is again used for a short time. The glass is then ready for edge-grinding.

CHAPTER VII.

GRINDING EDGE OF GLASS.—ROUNDING OF CORNERS.

In order that an efficient edge-support, which will be described later, may be given to the glass, it is desirable that the edge of the latter be ground truly circular and square with the face. The manner in which this is accomplished is shown in Plate VI. The glass lies upon three large blocks of wood, which hold it several inches above the surface of the circular iron plate. Thin oilcloth is arranged about the blocks and over the iron plate, to keep them dry. A smooth, flat, iron face-plate is mounted (so as to rotate in a vertical plane) on a heavy lathe head-stock; the latter is carried upon a strong slide which can be moved toward the glass by means of a fine pushing-screw. The lathe and face-plate are driven at a high rate of speed by means of a belt. In the case of the 5-foot glass the face-plate used was 24 inches in diameter and made 1,000 revolutions per minute. For a 24-inch glass, 3½ inches thick, a face-plate 11 inches in diameter, making 1,800 revolutions per minute, is used. A frame of wood, covered with oilcloth, is built around the face-plate, so that the grinding materials will not be thrown about the room. The glass rotates slowly with the turntable, as usual. Emery and water, or sand and water, are heaped upon the horizontal surface of the glass, and are slowly scraped toward and over the edge, so as to come between the revolving face-plate and the glass; a small jet of cold water, brought from the hydrant by means of a rubber tube, greatly assists in the uniform feeding of the emery, and also in preventing the generation of heat. But there is in reality no danger of heating, for the revolving face-plate *never actually touches the glass.* As the irregularities of the edge are ground away the face-plate is gradually moved forward by means of the slide and pushing-screw.

If the edge of the rough disk be very irregular, as is usually the case, the surface of the iron face-plate will have a circular groove worn in it, by the time the rough-grinding of the edge is done; in this case the face-plate should be turned flat and true again, and smoothed on a flat iron grinding-tool, before the edge of the glass is fine-ground. Several fine grades of emery are now prepared by the process of washing to be described later, and the edge-grinding is finished by the use, in succession, of three such grades of emery as flour, three-minute washed, and ten-minute washed. Care should be taken throughout the process that the edge of the glass is ground square with the face; any error in this respect can be corrected by slightly raising or lowering the outer end of the slide which supports the lathe head-stock.

Edge-grinding is accomplished very quickly in the manner described. The edge of a 24-inch disk four inches thick, even when very rough and irregular, has been ground and smoothed in ten hours of actual grinding. Despite the great speed of the rotating face-plate, I have never had any chipping of the glass or accident of any kind occur.

Before beginning the fine-grinding of the face and back it is well to round the corners at the edge of the glass. This is done by means of a smooth flat strip of sheet-brass of the size and shape of a large flat file; this is worked over the corners of the glass by hand, while the disk rotates slowly, emery and water being used for cutting. A "quarter-round" corner is usually made. Finer and finer grades of emery are used for smoothing the quarter-round. This rounding and smoothing are very necessary, as particles of glass from a sharp or rough edge are liable to be drawn in upon the surface by the action of the grinding tool during fine-grinding.

The wooden blocks are now removed and the glass replaced upon the carpeted turntable.

CHAPTER VIII.

FINE-GRINDING AND POLISHING THE BACK OF THE MIRROR.

Before discussing the work of fine-grinding I shall describe briefly the making of the fine grades of emery. I never buy finer grades than "flour." The latter grade is used with the full-size flat grooved tool to give a moderately fine surface to the glass after the rough-grinding previously described has made the front and back approximately flat and parallel. The residue of emery, fine ground glass, and water, resulting from the grinding with flour emery, is caught in buckets, as previously described. This residue is mixed with an abundance of water, in (for a large mirror) three or four clean granite-ware buckets, which are marked *A*. The contents of these buckets are thoroughly stirred, and are allowed to settle for two minutes; during this time all coarse particles will have settled to the bottom, and "two-minute" emery and finer grades remain in suspension in the water. The liquid is now quickly siphoned off, by means of a rubber tube, into other clean granite-ware buckets marked *B*, from which the handles have been removed. The contents of the latter are allowed to settle for four minutes, when the greater part of the liquid in each is carefully poured back into the buckets *A*. The contents of the latter buckets are reserved. The sediment remaining in the buckets *B* is the "two-minute" washed emery, with which the fine-grinding of the back is begun. After the grinding with this grade is finished, the residue from this grinding is mixed with what was reserved in the buckets *A*, the whole is stirred again and allowed to settle for five minutes, the liquid is siphoned off, and thus "five-minute washed" emery is secured. In a similar manner emeries which have remained in suspension in water for 12, 30, 60, 120, and 240 minutes are secured. In this way the large quantities of the finer grades which are necessary for large work can be secured as the work progresses. If accumulations of residues from previous work are available, some time will be saved by washing out all of the fine grades desired before the fine-grinding is begun.

Plane and concave mirrors are finished approximately flat on the back, as this form is most convenient for the application of the support-system. Fine-grinding of the back is usually done with the full-size, flat grooved tool, as this works rapidly. In this part of the work, in which the greatest refinement is not necessary, it is my custom to use the fine grades of emery (when these have all been prepared in advance) in succession, without stopping the machine or taking off the tool between grades for the purpose of cleaning the tool and the glass. The emery and water are supplied through the wooden cups at the back of the tool.

For a 24-inch mirror and its full-size tool, strokes varying from 6 to 8 inches in length are used with the 2-, 5-, and 12-minute washed emeries; shorter strokes, from 4 to 6 inches in length, are used with the finer grades. Considerable lateral displacement of the tool, amounting at the greatest to 2 or 2½ inches on the glass, is given at short intervals, by means of the transverse slide. On an average 20 double strokes per minute are given in fine-grinding a 24-inch mirror with full-size tool. Between 7 and 8 double strokes occur for each revolution of the glass and turntable.

With regard to counterpoising the tools during fine-grinding, the following statements may be made: My full-size iron tools for a 24-inch mirror weigh about 150 pounds, or $\frac{1}{3}$ pound for each square inch of area. This weight, or even $\frac{1}{2}$ pound to the square inch, is not objectionable with emeries down to 5-minute or 10-minute washed; but when this weight is allowed with finer emeries, scratches are liable to occur; indeed, with 30-minute washed and all finer grades they are almost certain to occur. The pressure on the glass is therefore decreased, by counterpoising the tool, to approximately $\frac{1}{5}$ pound to the square inch for 12- to 20-minute emeries, $\frac{1}{8}$ pound per square inch for 30- to 60-minute emeries, and about $\frac{1}{12}$ pound per square inch for 120- and 240-minute emeries. *This rule is followed, approximately, in all fine-grinding, whether of back or face.* This obviates, to a great extent, the danger of scratches in grinding, provided that thorough cleanliness is practiced in the preparation and use of the fine emeries. The apparatus by which the counterpoising is effected has already been described (page 5).

In fine-grinding a 24-inch glass, the 2-minute and 5-minute emeries are used for three-quarters of an hour each; the 12- and 30-minute emeries for one hour each, and the 60-, 120-, and 240-minute emeries for one and one-half hours each. The fine-ground surface resulting is so exquisitely smooth that it takes a full polish very readily.

The back of the glass is now ready to be polished. This is done with a half-size or two-thirds size polishing tool, which is moved about on the glass by the action of the machine precisely as a half-size grinding-tool would be. Optical rouge and distilled water are used, instead of emery and water. The work of polishing will be described in detail later, in connection with the work of finishing the face of the glass.

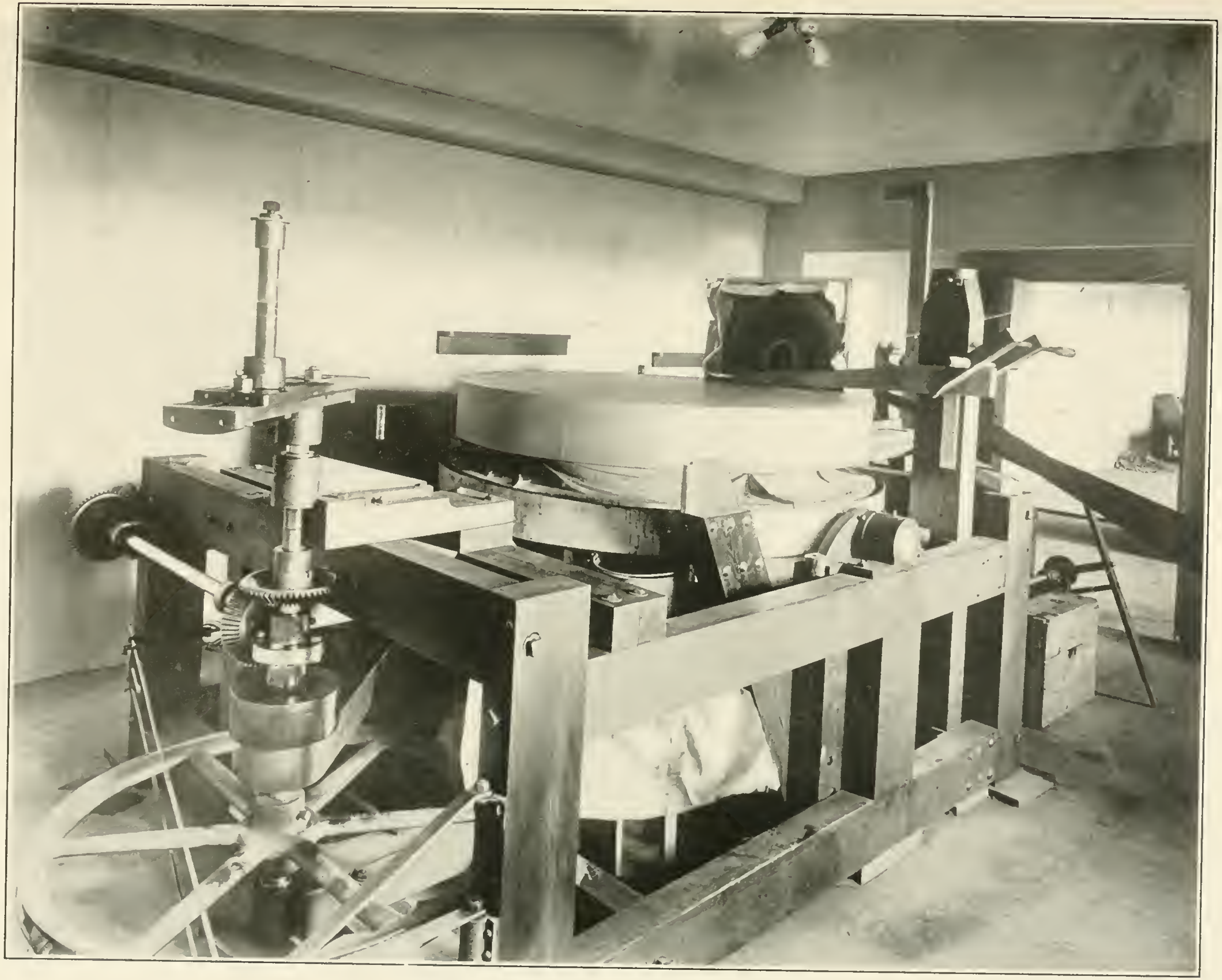
It is an excellent plan to fine-grind and polish the front surface of a disk also, approximately flat, as has been described for the back; the optician is then able to examine carefully the internal structure of the disk. Usually there is no choice as to which side shall be used for the face of the mirror, but this can readily be determined when both sides are polished. Plate VII shows the 5-foot disk with both sides ground and polished in this manner.

CHAPTER IX.

GRINDING THE CONCAVE SURFACE.

As before stated, it is my practice to use full-size grinding tools for concave mirrors up to 24 or 30 inches in diameter. For larger concave mirrors half-size tools are generally used. I shall first describe the grinding of a 24-inch concave.

The glass must be carefully *centered* by means of the three adjustable arcs attached to the supporting plate; these arcs must not be screwed tightly against the glass, lest the latter be strained; several thicknesses of heavy drawing paper are used between arcs and glass.



FIVE-FOOT MIRROR AND GRINDING MACHINE.
METHOD OF GRINDING EDGE OF GLASS.

The glass must also be carefully *levelled* (by means of the three large adjusting screws of the turntable) so that its upper surface is accurately at right angles to the axis of rotation; this is determined by rotating the turntable, and trying the surface with a surface-gauge. The band of thin oilcloth is securely bound around the edge of the glass, to keep the polished back and the cushion clean and dry.

The excavation of the concave is begun with moderately coarse emery (if the concave is to be quite deep) and a lead tool; this is a lead disk about 10 inches in diameter and $1\frac{1}{2}$ or 2 inches thick; it is easily turned in a lathe to the proper curvature; it is used on and near the center of the glass until a depression of approximately the desired curvature (as determined by the spherometer) and of 12 or 13 inches diameter is produced. A heavy iron tool about 13 inches in diameter, which has been turned and ground to the proper curvature, is now put on with about No. 90 emery. By giving careful attention to the length of stroke, and to the position of the tool on the glass as determined by the setting of the transverse slide, and by frequent trials of the curvature of the excavation with the spherometer, the diameter of the excavation is gradually increased, while its *curvature* is continually kept very near that which is desired for the finished mirror; this keeps the iron tool of proper curvature also.

The stroke used in this work should vary from 6 to 10 inches in length. As the size of the excavation increases, the setting of the transverse slide is continually changed so that the tool acts farther and farther to one side of the center of the glass; otherwise the radius of curvature will be shortened. When the diameter of the excavation has increased to about 22 inches, flour emery is substituted for the No. 90, and the grinding is continued as before. Care is now taken to make the curvature read exactly right with the spherometer. When the excavation becomes about 23 inches in diameter, the 13-inch tool is taken off, and the full-size, convex, grooved iron tool is put on; this has previously been fine-ground to the proper curvature on the corresponding concave tool. With this tool and washed flour emery the diameter of the concave on the glass is increased to $23\frac{5}{8}$ or $23\frac{3}{4}$ inches.

The fine-grinding or smoothing of the concave is now done with the full-size tool. The same grades of emery, the same lengths and speed of stroke, and the same rules in regard to counterpoising are used as have already been described in the case of fine-grinding the back of the glass (page 13). The length of stroke is changed every eight or ten minutes, and the lateral displacement of the tool (given by means of the transverse slide) is changed slightly at the end of every two or three complete revolutions of the glass. The tool is taken off after each grade of fine emery is used, and the tool and glass are carefully cleaned. With the assistance of the counterpoise lever the removal of the tool is effected easily and safely, without disconnecting it from the main arm of the machine; this is well shown in Plate IV, in which the grinding tool is shown hanging at one side of the glass.

The surface of the glass is examined with a microscope after each grade of emery is used, to make sure that no pits from previous grades remain.

During all fine-grinding and machine-polishing a large sheet of heavy clean paper or pasteboard is attached to the main arm in such a way that no particles of dust from the belts which control the slow rotation of the tools can fall upon the glass.

The process of grinding larger concave surfaces without the use of full-size tools is precisely similar to that described for a 24-inch mirror, up to the point of substituting the 24-inch convex tool; from this point the grinding is carried on by a continuation of the use of a half-size, convex grooved tool; this may be the same iron tool which has been used for enlarging the excavation. When the diameter of the excavation approaches that of the glass, the tool should be tested with the spherometer for curvature, and, if necessary, ground in its corresponding concave iron tool until its curvature is uniform and of exactly the desired radius. The grinding of the glass is then continued with washed flour emery until the edge of the excavation is within $\frac{1}{8}$ inch of the edge. Experience in the previous use of the half-size tool, in enlarging the excavation and in keeping the curvature of the glass uniform and of the desired radius, will enable the optician to decide upon the various lengths of stroke and the various settings of the transverse slide necessary in this grinding and in the finer grinding to follow.

In fine-grinding a 30-inch concave with a 16-inch tool, strokes varying from 6 to 12 inches in length are used; for a 9-inch stroke the *normal* setting of the transverse slide (*i. e.*, one which would tend neither to lengthen nor shorten the radius of curvature of the glass) would be such that the outer edge of the tool overhangs the glass about 3 inches in the forward stroke, while the inner edge of the tool passes about one inch on the other side of the center of the glass on the return stroke.

Throughout the entire process of fine-grinding with the half-size tool the length of stroke is changed once every eight or ten minutes; at the end of every two or three revolutions of the glass the setting of the transverse slide is changed, a little at a time, for a considerable distance on either side of the *normal* setting; the setting of the slide can be changed without difficulty, while the machine is running, by merely turning a hand-wheel. By these means the formation of zones of unequal focal length can be entirely avoided.

The same grades of emery are used, and the same rules in regard to counterpoising observed, as with full-size tools. Notwithstanding the fact that the length of stroke can be considerably greater than with full-size tools, each grade of emery must be used for a longer time, on account of the smaller area of the grinding surface. Glass and tool are thoroughly cleaned, and the surface of the former examined, after the use of each grade of emery, as before described.

Care must be taken during this work that the belts which rotate the turntable are kept tight, so that no irregularity in the rotation of the turntable with reference to that of the crank-shaft can occur. It is absolutely necessary that all of the fine work on large mirrors be done in rooms where no sudden changes of temperature can occur, and that nothing be allowed which might affect the temperature of the glass locally.

If the concave mirror is intended for a paraboloidal one, the fine-ground surface should be spherical, with its radius of curvature $2\ F + \frac{R^2}{4F}$, where F is the desired focal length of the finished paraboloid and R is the semi-diameter of the mirror; the reason for this is fully explained later. I have never attempted to parabolize while fine-grinding; it is possible that it might be well to do this in the case of very large mirrors of short focus, but my practice has been to fine-grind and polish to a spherical surface, free from zones, and then to parabolize by means of suitable polishing tools.

CHAPTER X.

POLISHING.

The preparation of polishing tools has already been described. The polishing rouge which I use is of the quality which is used in large quantities commercially in polishing plate-glass. I prefer the powdered form always. This grade of rouge is not expensive (it costs about 30 cents per pound), but, like all rouge which I have seen, it contains hard, sharp particles which may cause scratches. It must therefore be thoroughly washed in the following manner:

In a clean, deep bowl *C* enough rouge is placed to fill it about one-third full; the bowl is then nearly filled with distilled water. The mass is very thoroughly stirred with a clean wooden paddle, and allowed to settle for about twenty minutes. The water above the rouge will now be perfectly clear; this water is siphoned off. With a clean spoon the light and fine rouge constituting the upper one-third of the precipitated mass is removed, and placed in a second clean bowl *D*. The rouge remaining in *C* may be again stirred up with an abundance of distilled water, and allowed to settle as before, the water siphoned off, and the upper one-fourth of the precipitated rouge removed and placed in *D*. The heavier rouge which remains in *C* is about half of the original quantity taken; this is usually reserved, and, after further washing, is used for polishing the backs of mirrors, and for similar work. Only the contents of the bowl *D* are used for fine work, and these are stirred up again and again with distilled water during the process of polishing, and only the fine, soft cream which remains on the top of the mass of rouge, when it settles each time, is used for polishing.

The thin cream of rouge and distilled water is applied to the glass by means of a wide brush consisting of a thin paddle of wood with clean cheese-cloth wrapped and tied about one end. Brushes of the usual kind should not be used.

By taking these precautions, and by the use of the wax surface on the rosin squares, scratches in polishing can be entirely avoided. It is true that the very light, fine rouge polishes more slowly than the heavier and coarser rouge, but an exquisitely fine polished surface is produced on the glass by its use. The wax surface also polishes more slowly than a bare rosin one, but it has the very great advantage that its action is more smooth and uniform than that of the rosin surface; the latter often tends to cling to the glass, and this unequally in different parts of the stroke.

The same question arises in regard to the size of polishing tools as in the case of grinding tools,—whether they shall be full-size or smaller. In the writer's opinion fine plane and spherical surfaces up to about 36 inches in diameter are best polished with full-size tools, which are moved by hand, by the optician and one or two assistants, upon the surface of the slowly rotating glass. The upper parts of the machine are, of course, removed during such polishing, which I shall call manual polishing.

A 24-inch polishing tool, prepared as already described, with its wooden basis $2\frac{3}{4}$ inches thick, weighs about 25 pounds; this is not heavy enough for the best action in polishing; so about 50 % additional weight is put on in the form of 12 lead blocks which are distributed uniformly and screwed to the back of the tool. This gives a weight of about $\frac{1}{12}$ pound for each square inch of area, which is found to work well for all large tools. For tools 18 inches or less in diameter somewhat greater pressure per square inch of area may be used. A 36-inch tool, with wooden basis $3\frac{3}{4}$ or 4 inches thick, weighs 75 or 80 pounds, and needs no additional weighting.

The work of polishing a 24-inch mirror with full-size tool will now be described. Six strong knobs of oak wood are screwed to the back of the wooden basis, each knob being at the center of weight of each sixty-degree sector of the tool. These knobs serve for pushing, pulling, and lifting.

The polishing tool, which, with the glass, should have cooled over night after the warm-pressing or rough-pressing previously described, is now to be cold-pressed. Cold-pressing is absolutely necessary in all fine work on large optical surfaces. In warm-pressing, both tool and glass are distorted by even slight warming, and when they become cool a perfect fit cannot be expected. The glass is carefully wiped with clean cheese-cloth, and an abundance of very thin mixture of rouge and water is spread upon it. The tool is now placed upon the glass and allowed to lie for several hours, being moved about slightly every ten minutes to redistribute the rouge and water, and to prevent the latter from drying around the edges. The pressing may be assisted at first by means of a 20- or 30-pound weight, the pressure of which *must* be distributed by some such means as three bars laid upon the six knobs, and a triangle, carrying the weight, laid upon these. The final cold-pressing must be done by the weight of the tool alone. The tool is taken off and examined occasionally; when it is sufficiently pressed the wax surface appears uniformly smooth and bright. So perfect a fit is secured in this way that there is no danger of injuring the form of the glass when polishing is begun. This applies to all stages of polishing and figuring. A fresh supply of rouge and water is now spread upon the glass.

The stroke of the 24-inch polishing tool is easily given by the optician and one assistant, who sit on opposite sides of the machine; the glass slowly rotates with the turntable, making about 2 revolutions per minute. The knobs on the back of the tool are held in the hands, and the stroke is given by alternately pushing and pulling; no vertical pressure whatever should be given by the hands. In addition, a considerable side-throw is always given, first to one side, then to

FIVE-FOOT MIRROR WITH FRONT AND BACK POLISHED APPROXIMATELY FLAT.
LOOKING THROUGH THE GLASS.

the other; this greatly assists in preventing the formation of zones of unequal curvature. Polishing may be begun with a stroke 6 inches in length, which of course causes the tool to overhang the glass 3 inches at the ends of the stroke; between 20 and 25 double strokes per minute are given. The side-throw used with this length of stroke is about 2 inches, *i. e.*, the tool is made to overhang the glass about 2 inches, first to the right, then to the left; the time occupied in passing from the extreme right to the extreme left is about what is required for 4 double strokes. This stroke and side-throw are continued while the glass makes exactly 2 revolutions; the tool does not rotate with the glass, of course, while the stroke is being given; the last stroke should end with the tool central upon the glass.

Tool and glass are now allowed to rotate together for $\frac{5}{6}$ of a complete revolution, and each optician then grasps the pair of knobs next to that which he held before, so that the stroke is now given along a diameter of the tool 60° from that last used; the length of stroke is now changed to 7 inches, and the side-throw to $2\frac{1}{2}$ inches, and polishing is again carried on during exactly 2 revolutions of the glass. Tool and glass are again allowed to rotate together for $\frac{5}{6}$ of a revolution, and polishing during 2 revolutions is now done with a stroke of 8 inches and side-throw of 3 inches. During the next periods of polishing, each of 2 revolutions of the glass, the stroke and side-throw are gradually shortened until a stroke of 4 inches or less is reached; then the length of stroke is increased again.

When polishing has been carried on during 6 or 8 periods of 2 revolutions each, it will be found necessary to supply more rouge. The only entirely satisfactory method of doing this, when a full-size polishing tool is used, is to remove the tool from the mirror, and quickly spread the thin cream of rouge and water upon the glass as uniformly as possible with the cheese-cloth brush. The removal of the tool is effected by the two opticians carefully sliding it off the mirror, and lifting at the same time. The tool should be allowed to remain off the glass for only as short a time as possible, so that the form of the latter shall not be altered as a result of a change of temperature of the surface, caused by evaporation. For this and other reasons, such as the prevention of dust, the air in the polishing room should be kept moist by keeping the floor well sprinkled.

When the tool is replaced on the mirror it is lifted by both opticians so that only a very small part of its weight remains on the glass, and is lightly moved about, for 30 seconds or more, to distribute the rouge and water thoroughly before polishing is continued. As before stated, the method just described is the only entirely satisfactory one, known to the writer, of supplying rouge during the polishing with a full-size tool. All methods of supplying rouge at the edge, or through holes in the tool, are inadmissible when the greatest refinement of figure is required.

It is in order that they may be easily handled in the manner described that full-size polishing tools should be made light. It would, of course, be possible to devise mechanism by which tools of any size and weight could be sufficiently counterpoised, could be moved about upon the glass, and could be removed from the latter for the purpose of supplying rouge. The simple and economical method which I have described, however, works well for mirrors up to 36 or 40 inches in diameter. For larger mirrors it is more economical, in the opinion of the writer, to use half-size tools for obtaining a fully polished spherical surface, and the same and smaller tools for parabolizing. The method of using these will be described later.

In general, it is much easier to prevent the formation of zones, and to eliminate zones already present, with full-size polishing tools than with smaller ones. The method of manual polishing just described, in which the length of stroke and the amount of side-throw are very frequently changed, tends to give a spherical surface, except for a zone around the edge of the mirror one-half an inch or less in width; this part of the surface will be of too great focal length, *i. e.*, will turn down or back slightly, unless means are taken to prevent it. This tendency is most pronounced when a long stroke is used to excess, or when the rosin squares are too soft. It is entirely prevented by diminishing the area of the rosin squares around the edge of the tool, by trimming their edges to such a form as is shown in Fig. 4, page 28. The exact amount of trimming required depends upon the length of stroke, hardness of rosin, and temperature of polishing room, and therefore can be exactly determined only by experience.

A 24-inch mirror which has been properly fine-ground with emeries down to 2-hour or 4-hour washed, is readily brought to a perfect polish with a full-size tool in from 2 to 4 hours of actual polishing. If several broad zones of different focal lengths have resulted from the fine-grinding, as frequently happens, these zones can be gradually eliminated by a continuation of the use of the full-size polisher as above described.

Attention must be given to the rosin squares, which gradually press down so that their edges must be trimmed to keep the grooves of their original width and of uniform width. When the bare rosin begins to show at the corners or edges of the faces of the squares, which will occur after 6 or 8 hours' use of the tool, a new coat of wax must be applied, and the tool must again be thoroughly cold-pressed. It must not be supposed, however, that cold-pressing is necessary only at such times; in all fine work this pressing must be done whenever the tool has remained off the glass for more than a few minutes; after hanging face down during the night the tool is always cold-pressed for about 2 hours before polishing is begun in the morning.

Polishing with half-size or smaller tools is best done with the machine, instead of by manual work. These tools do not have to be removed from the glass in order to renew the supply of rouge; they are therefore connected to the machine and used very much as half-size grinding tools are used; in my work they are made of such weight that they need not be counterpoised. Very large or unusually heavy polishing tools of this kind can, of course, be easily counterpoised when desired.

Great experience, constant attention to very frequent changing of the position of the tool by means of the transverse slide, and frequent testing of the form of the mirror surface are necessary in polishing with half-size or smaller tools, in order to preserve the uniform curvature of the surface. This is greatly facilitated by trimming the rosin squares at and near the edges of the tool, as in the case of full-size tools, but to a greater extent; the effect of the action of the edges of the tool is thus softened or blended.

When a half-size or smaller tool has just been coated with wax, or is known to be far from the exact form desired, it is first cold-pressed in the usual way on the center of the glass. But the final cold-pressing of such tools should be done as follows: The entire surface of the glass is painted with rouge and water, and the machine is set to give a "normal" stroke, *i. e.*, one by which the tool is made to cover the entire surface of the mirror as uniformly as possible (without an excess of action on any zone) as the glass revolves; the machine is run extremely slowly, and the setting of the transverse slide is changed often; after pressing the tool for an hour or two in this way, polishing or figuring is to be begun.

CHAPTER XI.

TESTING AND FIGURING SPHERICAL MIRRORS.

Before describing the work of figuring concave mirrors, which is done with polishing tools, it will be necessary to consider methods of testing. The principles involved in testing concave mirrors at their center of curvature by Foucault's method have been thoroughly explained and illustrated by Draper on pages 13–19 of his book, and by Dr. Common in his book *On the Construction of a Five-Foot Equatorial Reflecting Telescope.* Foucault's original paper on this subject may be found in Vol. V of the *Annals of the Paris Observatory.*

All mirrors, when being tested, are placed on edge, so that the axis of figure is nearly horizontal, large mirrors being suspended in a wide, flexible steel band, lined with soft paper or Brussels carpet; for glass mirrors larger than 30 inches in diameter it is very desirable to have the grinding and polishing machine so constructed that the glass can be turned down on edge for testing, in the manner shown on Plate II, without removing it from the machine. A 30-inch glass mirror 4 inches thick weighs about 260 pounds; mirrors larger than this are difficult to handle without suitable mechanism.

A small, brilliant source of light, or "artificial star" may be produced by placing in front of the flame of an oil lamp a thin metal plate in which a very small pinhole has been bored. If the illuminated pinhole be placed about an inch to one side of the principal axis of the mirror, and at a distance from the mirror equal to its radius of curvature, a reflected image of the pinhole will be formed on the other side of the axis, and at the same distance from it and from the mirror as the corresponding distances of the pinhole itself. If the surface of the mirror is perfectly spherical, and if there are no atmospheric disturbances in the course of the rays, the reflected image, when examined with an eyepiece, will be found to be a perfect reproduction of the pinhole, with the addition of one or more diffraction rings around it, minute details of the edge of the pinhole appearing as exquisitely sharp and distinct as when the pinhole itself is examined with an eyepiece. If the eyepiece be moved outside and inside of the focus, the expanded disk in both cases appears perfectly round. Nothing can be more impressive than to see such a reflected image produced by a fine spherical mirror having a radius of curvature of 100 feet or more. Several such mirrors of 2 feet aperture have recently been finished here.

The use of an eyepiece is interesting for such experiments as that just described, and is important as a check upon the test with an opaque screen. The latter test, however, which I shall call the knife-edge test, is used almost exclusively for mirrors of all forms; it is far more serviceable than the eyepiece test in determining the nature and position of zonal irregularities, and is far more accurate in determining the radius of curvature either of a mirror as a whole, or of any zones of its surface.

If the eye be placed just behind the reflected image of the illuminated pinhole, so that the entire reflected cone of light enters the pupil, the polished, unsilvered mirror surface is seen as a brilliant disk of light. Let an opaque screen or knife-edge be placed in the same plane through the axis as the pinhole, and be moved across the reflected cone *from the left*, and just in front of the eye; if a dark shadow is seen to advance across the mirror from the left, the pinhole and knife-edge are inside of the best focus, and must be moved together away from the mirror; if, however, with the knife-edge still moved across from the left, the shadow advances across the mirror from the right, pinhole and knife-edge are outside of the focus and must be moved toward the mirror. By repeated trials a position is found from which the shadow does not appear to advance from either side, but the mirror surface darkens more or less uniformly all over: this is the position or plane of the best focus, and it is with this position of the knife-edge that irregularities of the surface, if any exist, are seen in most highly exaggerated relief; with this position of the knife-edge, the mirror, if perfectly spherical, is seen to darken with absolute uniformity all over as the screen is moved across the focus, and the impression of a perfectly plane surface is given to the eye.

If, however, the mirror is not perfectly spherical, but contains several zones of slightly different radii of curvature, a very common case, these zones will appear as protuberant or depressed rings on an otherwise plane surface. The reason for this is evident; the light from some parts of such zones is cut off by the knife-edge *before*, from other parts *after*, the illumination from the general surface is cut off; the surface is therefore seen in light and shade, *i. e.*, in enormously exaggerated relief. The mirror must be regarded as being illuminated by light shining very obliquely along the surface from the side opposite that from which the knife-edge advances across the focus. The interpretation of lights and shades becomes easy after a little experience; not only is the character of a zone—whether it is an elevation or depression—readily seen, but its diameter and its width are readily determined.

If the disk of glass is of sufficient thickness and of proper quality, and if attention has been given to the uniform rotation of the turntable and to the protection of the glass from abnormal conditions of temperature during grinding and polishing, all irregularities of figure which occur are perfect zones or rings concentric with the edge of the glass; that is, the surface is always a perfect surface of revolution. If, however, these precautions have not been taken, or if the glass has been improperly supported during grinding and polishing, or if it has been cut out of thick *rolled* plate-glass, so that it is weak in the direction of one diameter, an astigmatic mirror may be produced, in which the radius of curvature is slightly different along two diameters at right angles to each other.

Astigmatism is easily recognized with either the knife-edge or the eyepiece test. Let the plane of the apparent focus be determined with the knife-edge advancing from the left, then from above, then from the right, then from a number of directions between these three; if astigmatism exists the planes of the various foci thus found will not coincide; and the directions of greatest and least curvature of the surface are readily determined. When the eyepiece test is used, an astigmatic mirror does not give a sharp image even at the best focus; if the eyepiece be moved outside and inside of this focus the expanded disk becomes elongated, and is not uniformly illuminated; the direction of elongation outside is at right angles to that inside, and the distribution of light in the expanded disk is entirely different outside and inside of the focus.

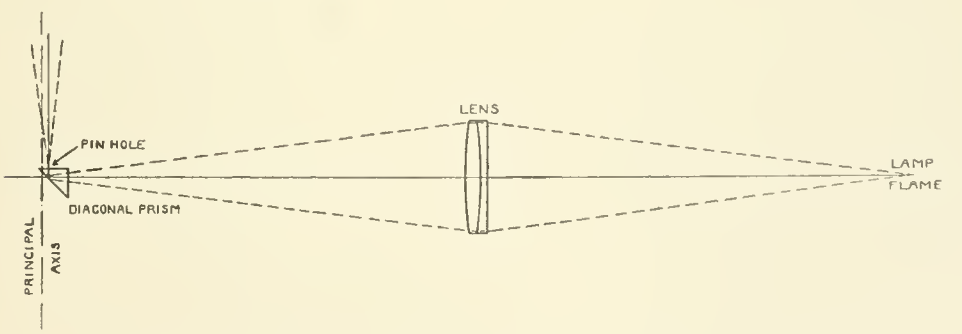


FIG. 1.

ARRANGEMENT BY WHICH ARTIFICIAL STAR IS USED VERY CLOSE TO OPTICAL AXIS.

The general character of the tests having now been described, let us consider some important matters of detail which are necessary for the greatest refinement in testing all forms of mirrors.

By the use of a small lens and a diagonal prism, in the manner shown in Fig. 1, the lamp can be kept well out of the way, and the illuminated pinhole and its reflected image brought very near to the axis of figure of the mirror. This is of much importance in testing mirrors of short focus or of great angular aperture, as the danger of errors in testing due to working considerably out of the axis of figure is avoided. As may be seen in the figure the pinhole is now placed at the surface of the diagonal prism nearest to the mirror being tested. The arrangement should be such that the cone of rays proceeding from the lens is considerably larger than is needed to fill the concave mirror.

When being figured, mirrors are usually tested while unsilvered, since very frequent tests are desirable. While the amount of light reflected from the polished unsilvered surface is surprisingly great, a much more brilliant "artificial star" than that given by the oil lamp is required for the greatest refinement and accuracy with the knife-edge test, especially in the cases of plane, paraboloidal, and hyperboloidal mirrors, in which there are two reflections from the unsilvered surface. It might be supposed that a larger pinhole could be used, and thus a more brilliant illumination of the mirror surface secured; but a large pinhole allows an apparent diffusion of light over the mirror surface, which obliterates all the more delicate contrasts of illumination due to minute irregularities of surface. With feeble illumination of the surface the eye is entirely unable to detect slight contrasts, which with brilliant illumination become strong and unmistakable. When the knife-edge test is used with an extremely small pinhole of between $\frac{1}{250}$ and $\frac{1}{500}$ inch in diameter, illuminated by acetylene or (what is much better) oxy-hydrogen or electric-arc light, minute zonal irregularities are strongly and brilliantly shown, which are entirely invisible with large pinhole or insufficient illumination. With the arrangement of lens and diagonal prism (Fig. 1) either of the sources of light named can be used without difficulty; disturbances of the air from their heat should be prevented by placing the light behind a partition with a window of thin plate glass.

With the best conditions of apparatus just described, the degree of accuracy to be attained with the knife-edge test is surprising. With a mirror of 2 feet aperture and 50 feet radius of curvature, the plane of the center of curvature can be easily located to within $\frac{1}{100}$ inch, and with care to within half of that amount. With the dimensions given, a change of $\frac{1}{100}$ inch in the radius of curvature corresponds to a change of $\frac{1}{500{,}000}$ inch in the depth of the curve of the mirror surface. There can be no doubt that zonal irregularities of surface of half of this amount are readily recognized.

We are now ready to consider the finishing of a spherical mirror. As before stated, a continuation of the use of the full-size polishing tool tends toward the gradual elimination of zonal irregularities. This work is often slow and laborious, however, for when the mirror becomes nearly finished, so that any zones, when seen with the knife-edge test, appear as extremely slight elevations or depressions, the improvement becomes exceedingly slow. The work may be facilitated by the local use of very small polishing tools upon protuberant zones. These tools are usually from 2 to 4 inches in diameter, and consist of squares of rosin upon a basis of brass; their faces are waxed and cold-pressed, and the squares around their edges are trimmed in order to soften or blend the action of the edges; small local tools with their surfaces trimmed as shown in Fig. 13 (in which the shaded parts represent the rosin) are excellent for the purpose. These local tools are used as follows: the positions and width of any protuberant zones are carefully determined by the knife-edge test, and the glass is replaced on the rotating turntable; stationary pointers are clamped to the machine, and overhang the glass so as to indicate the exact positions of the zones; the surface is painted all over with rouge and water, and the optician works the small tools on the high zones by hand; the rubbing is done on each zone during several revolutions of the glass, the length and direction of the stroke being changed after each complete revolution. Great care and judgment must be used in this work, and the surface must be tested very often, otherwise a wide zone will usually give place to several narrow ones. After the protuberant zones have been softened down in this way the full-size polisher is again used for finishing the surface.

A large and perfect spherical mirror is an indispensable part of the equipment of an optical laboratory, as it affords what is in my opinion the most satisfactory means of testing large plane mirrors. On account of the ease of rigorously testing a concave spherical surface, this is the form which should be first attempted by beginners in optical work.

CHAPTER XII.

GRINDING, FIGURING, AND TESTING PLANE MIRRORS.

The making of large plane mirrors of fine figure is usually regarded as much more difficult than that of large concave mirrors. The difficulty has been, in the past, largely one of testing. With a satisfactory method of testing the large plane surface *as a whole*, in a rigorous and direct manner, the problem is greatly simplified. So far as the writer is aware, no such test has hitherto been fully developed. In *Monthly Notices*, Vol. 48, p. 105, Mr. Common suggests, very briefly, the testing of plane mirrors in combination with a finished spherical mirror, and gives a diagram in illustration; but no details in regard to the method are given. This method has been developed and used for many years by the writer in testing plane mirrors up to 30 inches in diameter. When this test is used, the difficulty of making a 24-inch plane mirror which shall not deviate from perfect flatness by an amount greater than $\frac{1}{500,000}$ inch is neither greater nor less than that of making a good spherical mirror of 2 feet aperture and 50 feet radius of curvature, when it is required that the radius of curvature shall not differ from 50 feet by a quantity greater than $\frac{1}{100}$ inch.

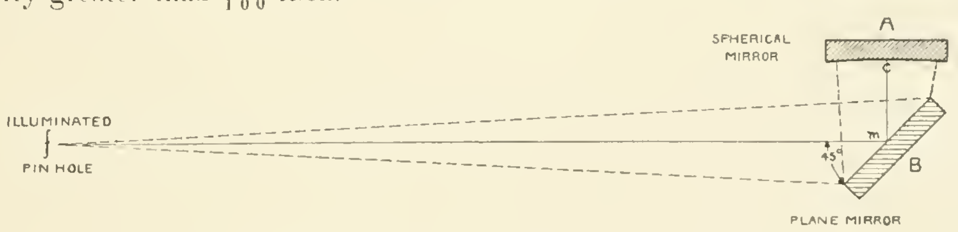


Fig. 2. Diagram Illustrating Testing of a Plane Mirror.

A spherical mirror A (Fig. 2), which should not be smaller in diameter than the plane mirror B to be tested, is figured with the utmost accuracy, special care being taken that no astigmatism, however slight, exists in it. The mirror A is silvered; B is polished and unsilvered. The mirrors may be set up as shown *in plan* in Fig. 2, the distance $cm + mf$ being equal to the radius of curvature of A; both mirrors hang on edge in steel bands as already described. The light proceeding from the illuminated pinhole strikes B, is reflected to A, thence back to B, thence to a focus close beside the illuminated pinhole.

When using the knife-edge test the optician sees the mirror B brilliantly illuminated, and in elliptical outline, the horizontal diameter appearing foreshortened by an amount depending upon the angle at which the mirror is viewed. With the knife-edge test the surface of B is seen in relief, as a whole; any zonal errors appear enormously exaggerated, and their character and position are readily determined, just as when a spherical mirror is tested at its center of curvature; these zonal errors, of course, appear elliptical, on account of their foreshortening; their effect is doubled in intensity on account of the two reflections from B (assuming that the illumination is as brilliant as the eye requires).

The test, as already described, is all that is necessary for the detection and location of zonal errors. But something more is necessary in order to detect general curvature, *i. e.*, convexity or concavity, in B. Let us assume that the mirror, when fine-ground and polished, is so nearly flat that no curvature can be detected with a Brown and Sharpe steel straight-edge of the finest quality; and for convenience in description let us also assume that the surface is free from zonal errors. Let the knife-edge be moved across the reflected cone from the left; a focal point is found at which the right and left sides of the mirror darken simultaneously; this focal point we will call f_1. Now let the knife-edge be moved across the cone from above, instead of from the left; a focal point will be found at which the upper and lower parts of the mirror darken simultaneously; this focal point we will call f_2. It is only when the mirror B is a perfect plane that f_1 and f_2 coincide with each other and with the point f (see figure). If B is slightly convex, f_1 and f_2 are outside of f (*i. e.*, farther from the mirror than f) and f_1 is outside of f_2. If B is slightly concave both f_1 and f_2 are inside of f, and f_1 is inside of f_2. In practice, the exact position of f is not found (except incidentally when the plane mirror is finished), for this would involve the very accurate measurement of the large distance $cm + mf$. The determination of the positions of f_1 and f_2 with reference to each other is all that is needed.

That f_1 and f_2 do not coincide when B is convex or concave is due to the fact that the curvation of B is apparently increased or exaggerated in the direction of the horizontal diameter of the mirror, on account of its foreshortening in this direction, as seen from f; while the curvature in the direction of its vertical diameter is not thus exaggerated. The effect is precisely as if the spherical mirror A were astigmatic, the parts of the surface adjacent to the horizontal diameter having a different radius of curvature from those adjacent to the vertical diameter. This effect is so marked that an extremely small deviation of B from a true plane can be detected. For example, if A and B are each two feet in diameter, the radius of curvature of A being fifty feet as before, and if the angle which the line fm subtends with the surface of B is 45°, a deviation from a true plane of $\frac{1}{350,000}$ inch in the surface of B is readily detected. If the angle of the mirror B be changed to 30°, as shown in Fig. 3, the accuracy of the test for general curvature is about doubled; the latter position, however, is not usually so convenient for determining the positions of zonal errors; for the greatest refinement, therefore, the stand on which A and B are supported is so designed that the positions of the mirrors can be quickly changed so as to give the greatest accuracy in each part of the test.

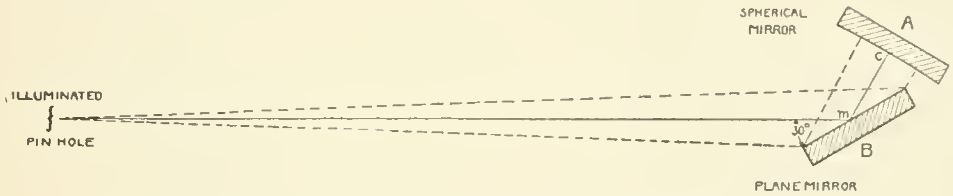


FIG. 3. DIAGRAM ILLUSTRATING TESTING OF A PLANE MIRROR.

The use of an eyepiece in this test is important because it shows how fatal to good definition is even a very slight convexity or concavity of a plane mirror when used in oblique positions. If f_1 and f_2 coincide as closely as can be detected with the knife-edge test (B being free from zonal irregularities also) the reflected image of the pinhole, as seen in an eyepiece at f, is as exquisitely sharp and perfect as if it were formed by the spherical mirror A alone. But if B is slightly convex or concave the appearance of the eyepiece image is similar to that which has already been described in connection with astigmatic concave mirrors; the image is not sharp even at the best focus; if B is convex, the image becomes elongated in a vertical direction outside, and in a horizontal direction inside, of the best focus; if B is concave the directions of elongation are the reverse of these.

The preparation of grinding tools for plane mirrors is similar to that of tools for concave mirrors. Three full-size, flat iron tools are usually made, however, all of which are grooved. These are ground together with carborundum of finer and finer grades, until all appear flat when tested with a carefully kept Brown and Sharpe steel straight-edge of best quality.

The plane mirror is fine-ground in the manner described for concave mirrors. It is of course a rare occurrence to find a large plane mirror nearly optically flat when it is first tested after grinding and polishing. My large mirrors almost invariably come out slightly convex when first polished; this may be due in part to the fact that the flat grinding tool becomes very slightly concave during the fine-grinding of the glass, from being worked on top (see page 7). Slight convexity of the mirror at this stage of the work is much better than slight concavity, for it is much better and easier to remove a high center than a high edge, during the process of figuring with polishing tools.

Manual polishing with full-size tools should be employed when the mirror is not too large to allow this. The polishing is begun with the *normal* tool shown in Fig. 4, in which the grooves are of uniform width throughout. After an hour's polishing the mirror is tested; if it is found to be convex, polishing is continued with the *concaving* tool shown in Fig. 5, in which all of the grooves are gradually widened toward the edges of the tool, so that there is a progressive decrease of action toward the edges of the glass; the amount of this widening must be

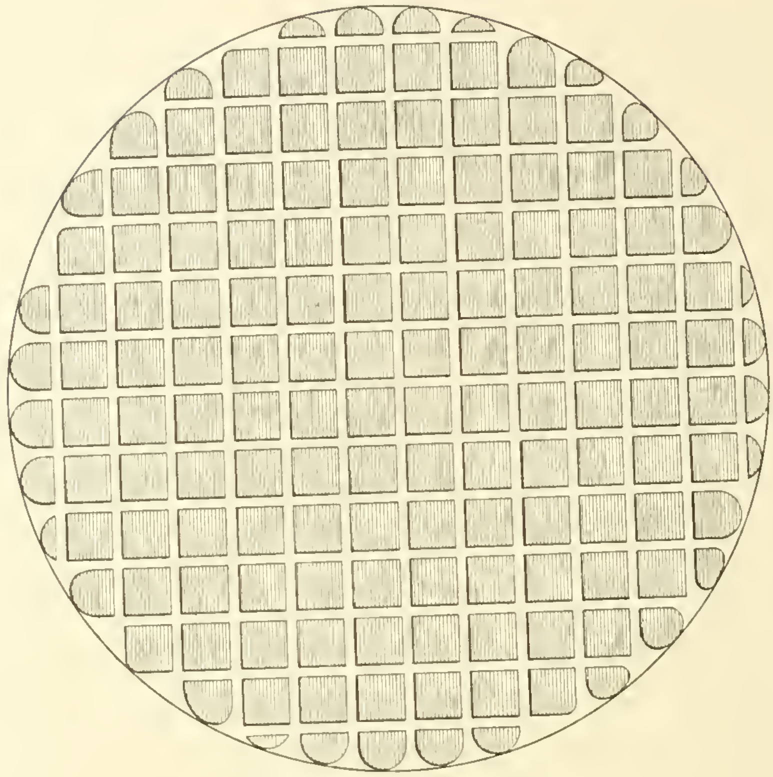


Fig. 4. Normal Polishing Tool.

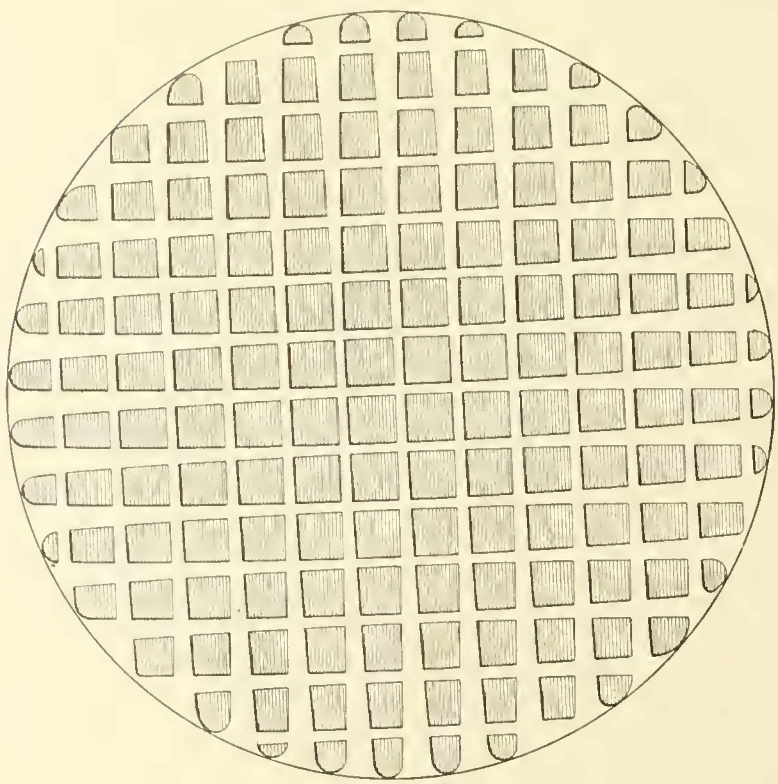


Fig. 5. Concaving Polishing Tool for Figuring Plane Mirror.

determined by experiment; it should be such that the convexity of the mirror is slowly and uniformly decreased.

If the mirror, when first tested, is found to be concave, the *convexing* tool shown in Fig. 6 is used to continue the polishing.

The concaving and convexing tools often tend to introduce broad slight zonal errors; hence recourse must be had repeatedly to the normal tool. When all trace of *general curvature* has disappeared, any remaining zonal errors are eliminated by the use of the normal tool, and, if necessary, of the small local or figuring tools, (see page 24).

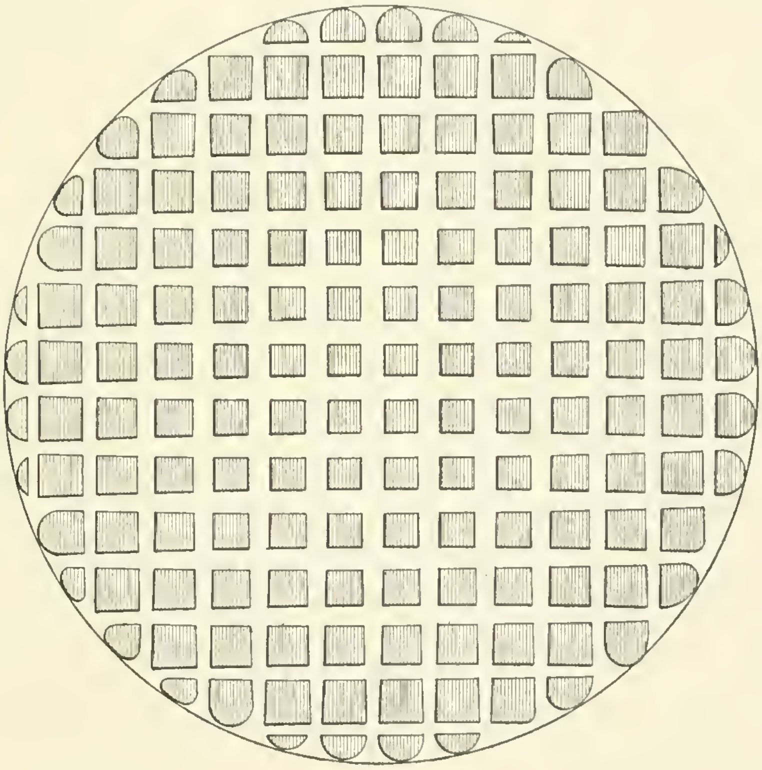


Fig. 6. Convexing Polishing Tool for Figuring Plane Mirror.

If a finished plane mirror is available which is not smaller than the one being figured, the work is very greatly facilitated by continually cold-pressing the polishing tools on the finished mirror; every precaution must be taken, however, to prevent injury to the figure of the finished mirror by such cold-pressing.

In some of the writer's early work, in which the thickness of mirrors was made only one-twelfth of their diameter, it was found that a *normal* polishing tool, as described above, tended to change the mirror very gradually toward a concave. This was undoubtedly due to the fact that the friction of polishing warmed the surface very slightly, thus expanding it and making it convex with reference to the polishing tool; the tool did not follow this change of form readily, hence the central parts of the glass were acted upon in excess. Furthermore, such thin mirrors, when unsilvered, were so sensitive to slight changes of temperature that the presence of the optician's body for a period of two or three minutes, at a distance of three feet from a mirror which was set up for testing, would throw a previously plane mirror convex by an amount many times greater than the smallest amount which can be detected by the knife-edge test. When the thickness of mirrors is made equal to about one-seventh of their diameter, their sensitiveness to all such temperature effects is very greatly decreased. Furthermore, in the case of silvered glass mirrors which are used for solar work, the writer has found that thick mirrors suffer very much less change of figure from exposure to the sun's heat than thin mirrors do. Silvering affords a great protection from changes of temperature, since the silver film furnishes an almost totally reflecting surface for heat radiations.

CHAPTER XIII.

TESTING AND FIGURING PARABOLOIDAL MIRRORS.

The work of changing a spherical mirror to a paraboloidal one is accomplished entirely by the use of polishing tools, by shortening the radii of curvature of the inner zones, instead of by increasing or lengthening those of the outer zones. The methods of effecting this change of curvature will be described after the methods of testing a paraboloid have been discussed.

Such testing can be done at the center of curvature, by determining there the foci or the radii of curvature of successive zones of the mirror; it may be done at the *focus* of the paraboloid, by the aid of a finished plane mirror which should be at least as large as the paraboloidal one; and it may be done directly on a star. The first two methods named have the very great advantage that they may be conducted without interruption, under the practically perfect atmospheric and temperature conditions of the optical laboratory.

Testing a Paraboloid at the Center of Curvature. A knowledge of the properties of the parabola enables the optician to compute the positions of the centers of curvature of successive, definite, narrow zones of the mirror, and the surface must be so figured that the radius of curvature of each zone agrees with the computed value. In testing, each zone in succession is exposed by means of a suitable diaphragm, all of the rest of the surface being covered. In practice, two entirely different formulæ may be used, depending upon the position of the illuminated pinhole.

Let F be the focal length of a finished paraboloidal mirror, and R the semi-diameter of any extremely narrow zone or ring of its surface, concentric with the vertex or center of the mirror; the normals to this zone cross the axis at a point whose distance from the vertex is $2\ F + \frac{R^2}{4\ F}$; hence, if the illuminated pinhole be placed very close to the axis, and at a distance of $2\ F + \frac{R^2}{4\ F}$ from the vertex, the rays of light reflected from the narrow zone will form a focus or image in the same plane (at right angles to the axis) in which the pinhole itself lies. This is the simplest formula which can be used, but it is not the most useful in practice.

In testing paraboloids at the center of curvature the writer has always used the following method and formula: The illuminated pinhole remains fixed at the center of curvature of the central parts of the mirror, *i. e.*, at a distance 2 F from the vertex, where F is the focal length. The intervals, measured along the axis, between the reflected foci of the various zones, are now twice as great as those given by the method described in the preceding paragraph; consequently these foci can now be determined with twice the accuracy which can be attained by that method. Only the rays reflected from the parts of the paraboloid very near to the vertex are now brought to a focus in the plane of the pinhole. If the paraboloidal figure is perfect, the rays reflected from any very narrow zone whose semi-diameter is R are now brought to a focus at a distance $\frac{R^2}{2F} + \frac{R^4}{16F^3}$ back of the plane the pinhole, *i. e.*, at a distance $2F + \frac{R^2}{2F} + \frac{R^4}{16F^3}$ from the vertex of the paraboloid. The quantity $\frac{R^4}{16F^3}$ is so small in the case of mirrors of moderate size and of ordinary ratios of aperture to focal length that it can be neglected; even in testing the outermost zones of the 5-foot mirror of 25 feet focal length, this quantity is less than 0.002 inch, while the quantity $\frac{R^2}{2F}$ amounts to $1\frac{1}{2}$ inches.

Now let us consider what is the best method of determining the planes of the reflected foci. Draper, Common, and other workers used an eyepiece for this purpose; this serves well for mirrors of moderate angular aperture, but for mirrors in which the ratio of aperture to focal length is as great as 1 to 5 or 1 to 6 this method presents serious difficulties; if narrow zones are used the image in the eyepiece is blurred and indistinct on account of the diffraction effect produced by the edges of the zonal openings in the diaphragm, while if wide zones are used the difference of focus of the inner and outer parts of a zone is so great that the image shows evidence of marked aberration; with neither narrow nor wide zones can the position of the focus be determined with very great accuracy.

In *Publications of the A. S. P.*, vol. xiv., No. 87, Hussey gives a formula for the position of the "circle of least confusion" when a zone of *given width* is used; if Hussey's formula were employed and the pinhole were made very small and round, with smooth edges, it is probable that much greater accuracy could be attained than by the use of an eyepiece in the ordinary way.

The method of locating the reflected foci which is used by the writer is as follows; it is capable of surprising accuracy when the optician has become experienced in its use. The reflected focus of a zone is found with the knife-edge, precisely as the focus of a spherical mirror is found. The knife-edge is moved across the reflected cone from the left; if the left side of the zone is seen to darken first, the knife-edge is inside of the focus; if the right side darkens first, the knife-edge is outside of the focus; when the right and left sides of the zone darken simultaneously, the knife-edge is at the focus of the zone. One advantage of this method is that it is independent of changes of focus of the eye itself; but the great advantage is that very narrow zones or arcs can be used. Diaphragms with zonal openings $\frac{1}{4}$ of an inch wide serve admirably for mirrors of 10 or 15 feet focal length; indeed the width of the zones which are actually used is considerably less than this; for, on account of diffraction, the edges of the openings in the diaphragms always appear as brilliant lines, even while the illumination near the center of the openings is being cut off by the knife-edge; it is therefore only the illumination near the center that is used in making the comparison.

The diaphragms which I use in this method of testing do not expose entire zones, but only pairs of arcs on the right and left sides of the mirror. Fig. 7 shows the diaphragm which was used in testing in this way the mirror of the two-foot reflector of the Yerkes Observatory. The arcs are cut in a long and narrow strip of thin metal; this is attached to the inner edges of two wooden strips, *a*; these

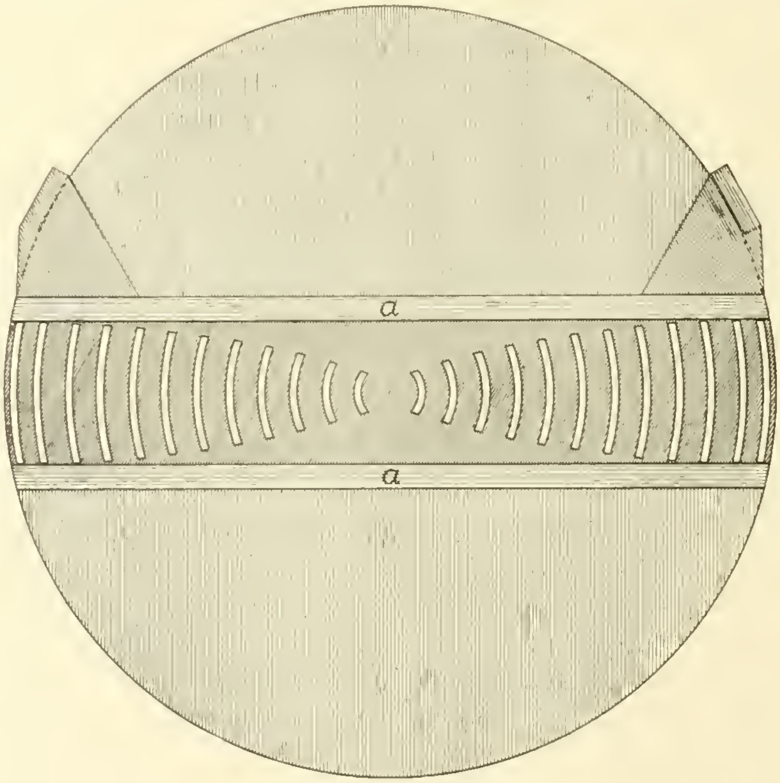


FIG. 7. DIAPHRAGM USED IN TESTING A PARABOLOIDAL MIRROR AT ITS CENTER OF CURVATURE.

edges are curved so that all parts of the thin metal diaphragm are nearly in contact with the curved surface of the mirror. The edges of the openings are bevelled so as to be extremely thin, and are finished dead-black. Twelve pairs of arcs were used, with mean radii of 1, 2, 3, . . . 10, 11, and $11\frac{7}{8}$ inches. The openings of these arcs are $\frac{1}{4}$ inch in width. The foci of the successive zones (except those near the center) can be readily determined by this means to within

$\frac{1}{500}$ inch along the axis, for a mirror of two feet aperture and of ten or fifteen feet focal length.

Care must be taken when testing in this way that the entire mirror surface is *uniformly illuminated* by the cone of light proceeding from the illuminated pinhole; this condition, once secured, is easily maintained, since the illuminated pinhole remains immovable.

I have described at considerable length the methods of testing paraboloids at the center of curvature, because of the importance of the subject, and because this will probably continue to be a favorite method, especially among amateurs. But when testing is done at the center of curvature, even with the extremely accurate method just described, the making of a large paraboloidal mirror of great angular aperture and really fine figure is an exceedingly difficult task. This is due in part to the necessity of very frequent tests, in each of which the foci of a large number of zones must be determined; it is due far more to the uncertainty in determining the exact nature of errors of surface (considering the surface as a whole) corresponding to focal readings which do not agree with the computed values. In the case of mirrors of small or moderate angular aperture, much important information can be gained by viewing the surface as a whole, from the (mean) center of curvature, by means of the knife-edge test; a finished paraboloid, when thus seen, appears to stand out in relief, in strong light and shade, as a surface of revolution whose sec-

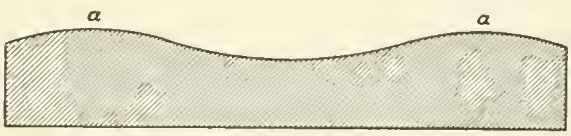


FIG. 8.

tion is that shown in Fig. 8; knife-edge and pinhole are both at the center of curvature of the zone a; the apparent curve of the surface should be a smooth one. But in the case of a mirror of large angular aperture the change of curvature is so rapid that only a narrow zone can be seen well at one time, *i. e.*, with a given focal setting of the knife-edge.

Testing a Paraboloid at its Focus. This method was briefly described by the writer in the *Astrophysical Journal*, November, 1901. It is incomparably more simple, direct, and rigorous than the test at the center of curvature. A well-figured plane mirror, which should not be smaller than the paraboloidal one, is necessary in order that the testing may be done in the optical laboratory. In practice a small diagonal plane mirror is also used, to avoid the necessity of a central hole through the large plane mirror. Both of the plane mirrors are silvered. The arrangement of mirrors is shown in Fig. 9. The diagonal prism is placed at f, with the illuminated pinhole very near the axis; pinhole and knife-edge are in the same plane, at a distance from the vertex equal to $c\,m + m\,f$, which is equal to the focal length of the mirror. The paraboloid is now tested as a whole, without the use of zones, precisely as a spherical mirror is tested at its center of curvature.

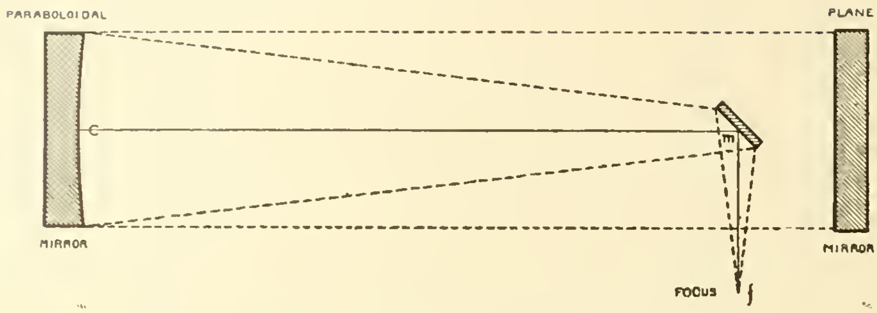


FIG. 9. TESTING A PARABOLOIDAL MIRROR AT ITS FOCUS.

If F be the desired focal length of the paraboloidal mirror whose semi-diameter is R, then the spherical surface which is fine-ground and fully polished preparatory to parabolizing should have a radius of curvature of $2F + \frac{R^2}{4F}$. This is because parabolizing is done by shortening the radii of curvature of all the inner zones of a mirror, leaving the outermost zone unchanged, as shown in Fig. 10; this is a far easier and better method in practice than to leave the central parts of the mirror

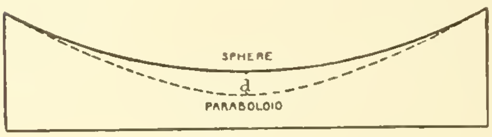


FIG. 10.

FIG. 11.

unchanged, and to lengthen the radii of curvature of all of the outer zones, as shown in Fig. 11.

Let us now suppose that the concave mirror shown in Fig. 9 is a *spherical* one with radius of curvature $2F + \frac{R^2}{4F}$, where R is the semi-diameter, and F is the distance $cm + mf$, from the center of the mirror surface to the plane of the pin-hole and knife-edge. If the spherical surface be now viewed from the point f with the knife-edge test, it will appear to stand out in relief, in strong light and shade,

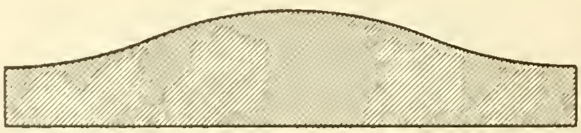


FIG. 12.

as a surface of revolution whose section is that shown in Fig. 12, the height of the protuberant center depending upon the angular aperture of the mirror. The reason for this appearance is readily seen by reference to Fig. 10. To change the spherical surface to a paraboloid, the protuberant center must be removed by the use of suitable polishing tools, until the surface, as seen with the knife-edge test from the point f, appears perfectly flat, *i. e.*, the illuminated surface darkens with perfect uniformity all over. As the paraboloidal surface nears completion, an elevated or depressed center, a "turned up" or "turned down" edge, or protuberant or depressed zones, can be seen and their character and exact position determined, with precisely the same ease and certainty with which similar irregularities are seen when a spherical mirror is examined at its center of curvation with the knife-edge test.

It should be noticed that even when the pinhole and reflected image are very near each other, as they should be, yet both may be far out of the axis of the paraboloid, if the mirrors are not properly adjusted or collimated; when this is the case the mirror surface, when seen with the knife-edge test, does not appear as a surface of revolution, and cannot be properly tested. The mirrors may be collimated by the following method, thus insuring that the pinhole and reflected image are both extremely near the optical axis.

The mirrors are set up approximately right by measurement. A ring about an inch in diameter, with two fine threads stretched diametrically across it, one vertical, one horizontal, is set up near the plane of the illuminated pinhole, the intersection of the threads marking the desired position of the optical axis. A light, stiff ring is made, which fits closely over the edge of the paraboloidal mirror, at the front; this ring can be slipped on and taken off as required. Two very fine bright wires are stretched diametrically across this ring, one vertical, one horizontal; these wires should be as close as possible to the face of the mirror; their intersection marks the position of the center or vertex of the paraboloid. Two fine short lines, one vertical, one horizontal, are scratched with a fine needle-point at the center of the silvered face of the small diagonal plane mirror. The eye is now placed about 3 feet outside of the plane of the crossed threads, and an assistant changes the inclination of the small plane mirror, by means of three adjusting-screws at its back, until the intersections of the threads, of the scratches, and of the wires are all seen in exact coincidence. The assistant next changes the inclination of the paraboloidal mirror (by means of three adjusting-screws at its back) until, with the eye in the same position as before, the intersection of the threads, the intersection of the wires, and the *reflection* of the intersection of the threads seen in the paraboloidal mirror, all appear in exact coincidence; the position of the axis of the paraboloid has now been defined. No attention is paid to the large plane mirror in this part of the work. The illuminated pinhole is now placed in position, and the large plane mirror is adjusted (by means of three adjusting-screws at its back) until the reflected image falls in the right position with reference to the axis and pinhole.

The frame which carries the paraboloidal mirror can easily be so designed that this mirror can be removed and replaced repeatedly, while figuring it, without sensibly disturbing the adjustments.

The difficulties of making short-focus paraboloidal mirrors of fine figure are so greatly reduced when this method of testing is used that I believe that the general adoption of this method by opticians would lead to such improvements in results as to bring about a marked advance in the usefulness of reflecting telescopes. The making of the large plane mirror which is necessary in this test becomes so simple and certain when the methods of testing and figuring described in the preceding chapter are used, that I have no hesitation in saying that when a large paraboloidal mirror of short focus and of the finest attainable figure is to be made, it is economical to make a plane mirror of the same size, with which to test it, if one is not already available. The concave mirror is first figured spherical and is used thus for testing the plane mirror while the latter is being figured; the plane mirror is then used in testing the concave one during the parabolizing of the latter. Both the plane and paraboloidal mirrors are then used in testing the small (convex) hyperboloidal mirror while the latter is being figured.

Testing a Paraboloid on a Star. With this method the mirror surface, as seen with the knife-edge test, presents the same general appearance as in testing in conjunction with a large plane mirror; in the latter test, however, errors of surface are

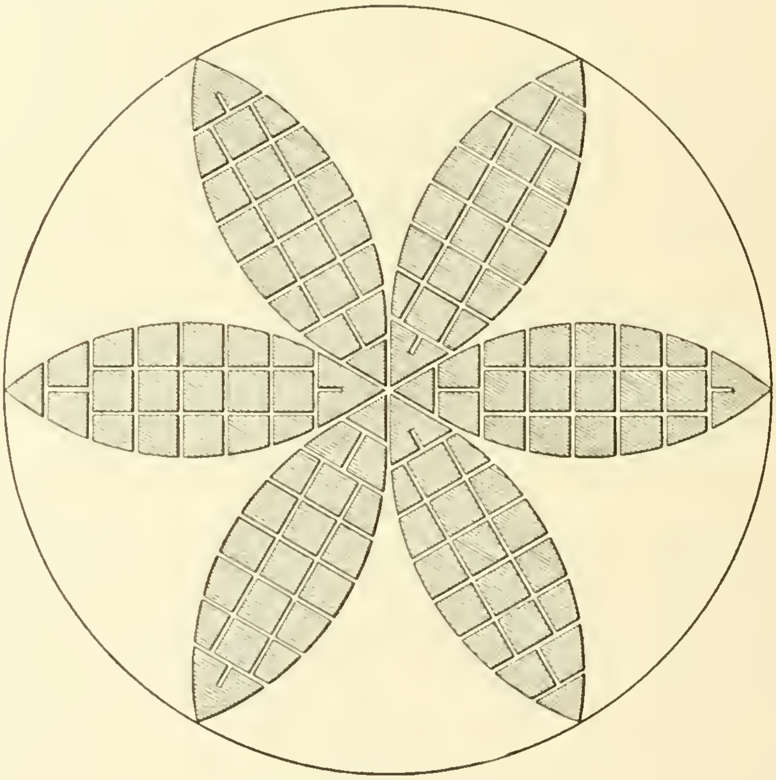


FIG. 13. FULL-SIZE POLISHING TOOL FOR PARABOLIZING.

seen in greater relief, because the effect of such errors is doubled on account of the two reflections from the paraboloid. In addition, it is impossible to overestimate the advantage of being able to test as often as is desired, in the optical laboratory, where atmospheric and temperature conditions can be controlled perfectly, and where the mirror does not have to be removed from the polishing machine in order to test it. In testing on a star it is seldom indeed that atmospheric conditions are sufficiently fine to allow any except the larger errors of surface to be seen.

Changing a Spherical Surface to a Paraboloid. As before stated, this is accomplished by shortening the radii of curvature of all of the inner zones of the surface, leaving the outermost zone unchanged (see Fig. 10). There are two distinct methods of accomplishing this: (1) by the use of full-size polishing tools, the rosin surfaces of which are cut away in such a manner as to give a large excess of polishing surface near the central parts of the tool; (2) by the use of small polishing or figuring tools worked chiefly upon the central parts of the mirror, and less and less upon the zones toward the edge.

(1) *Parabolizing with Full-Size Tools.* The rosin surface can be trimmed in a variety of ways to give a great excess of action on the central parts of the mirror. Fig. 13 shows one of the best forms of tool for this purpose, the shaded parts representing the rosin surface, coated with wax. The form of the edges of the rosin-covered areas can be altered as desired, and thus the amount of action on any zone can be in some measure controlled. Length of stroke and amount of side-throw are also very important factors in controlling the figure of the mirror. Tools of this kind serve admirably in parabolizing mirrors up to 36 or 40 inches in diameter, when the angular aperture is not very great.

(2) *Parabolizing with One-Third-Size and Smaller Tools.* In the case of very large mirrors, when full-size tools are almost unmanageably heavy, and in the case of mirrors of great angular aperture, in which the departure from a spherical surface is great and is effected with difficulty with full-size tools, one-third-size and smaller figuring tools may be used. The machine should invariably be employed in this work, the transverse slide being used to place the tool in succession upon the various zones. In order to preserve the surface of revolution the setting of the transverse slide should be changed only at the end of one or more complete revolutions of the glass. The rosin squares of the small tools should be somewhat softer than usual, so that the surfaces of the tools can accommodate themselves slowly to the slightly different curvatures of the successive zones. The squares around the edges of the tools should be trimmed, as before described, in order to soften the action of the edges. The mirror should be tested very often, and the utmost care taken to keep the apparent curve of the surface, as seen with the knife-edge test, a *smooth* one, *i. e.*, free from small zonal irregularities, at all stages of the parabolizing; this is not extremely difficult when the optician has become experienced in the use of the transverse slide.

The mirror of the 2-foot reflector of the Yerkes Observatory, which has a focal length of only 93 inches, was parabolized in this way by the writer. Two small tools were used, of 6 and 8 inches diameter respectively. The actual difference of depth, at the center or vertex of this mirror, between the paraboloid and the nearest spherical surface is almost exactly 0.0004 inch. This difference is unusually large in this case, on account of the exceptionally great ratio of aperture to focal length. This difference varies, in different mirrors, as the fourth power of the diameter of the mirrors, and inversely as the cube of the focal length. In the case of Lord Rosse's great mirror, in which the aperture is 6 feet and the focal length 54 feet (ratio 1 to 9) the corresponding difference at the center is only 0.0001 inch, very nearly. In the case of the 5-foot mirror of the Yerkes Observatory, of 25 feet focal length, the corresponding difference is about 0.0006 inch. This gives some idea of the actual amount of glass which must be removed by the figuring tools in parabolizing.

CHAPTER XIV.

TESTING AND FIGURING CONVEX HYPERBOLOIDAL MIRRORS.

The methods of figuring and rigorously testing convex hyperboloidal mirrors are now so thoroughly developed that the reflecting telescope can be regarded as a universal photographic telescope of the highest class, capable of giving, at the focus of the paraboloidal mirror of large angular aperture, the finest photographs now attainable of large and excessively faint objects such as the nebulæ in general; while by the addition of a small convex mirror a great equivalent focal length is obtained for the photography of bright celestial objects requiring large scale, such as the moon, the planets, the dense globular star clusters, and the annular and planetary nebulæ. The convex mirror of course serves as an amplifier, and possesses the great advantages over a lens used for this purpose that the perfect achromatism and the high photographic efficiency of the reflector are retained, and that the mechanical arrangements are very compact and economical. In order to give perfect definition the convex mirror must be an hyperboloidal one.

The writer has recently made two convex mirrors of different curvature, for use with the 2-foot reflector. These give equivalent focal lengths of 27 and 38 feet respectively.

Fig. 14 shows the arrangement of mirrors employed in the 2-foot reflector when used as a Cassegrain; a small diagonal plane mirror is used at m, to avoid the necessity of a hole through the center of the large concave mirror. P is the paraboloidal mirror, with its focus at f; H is the hyperboloidal mirror, the secondary

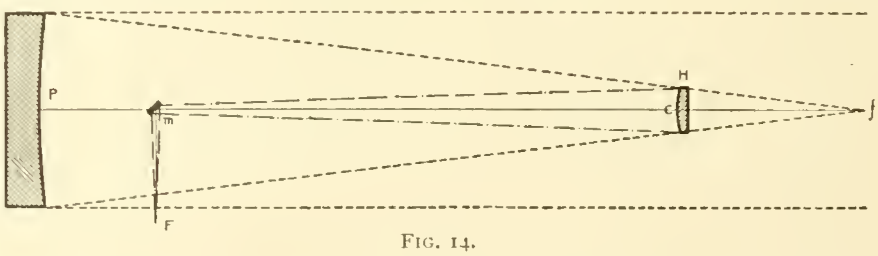


Fig. 14.

focus or magnified image produced by the combination being at F; the point c is the center of the hyperboloidal surface. Calling the distance $fc = p$ and the distance $cm + mF = p'$, then $\frac{p'}{p}$ represents the amount of amplification introduced by the convex mirror. The radius of curvature R of the spherical surface to which the convex mirror is ground and polished preparatory to hyperbolizing is found with sufficient accuracy for all practical purposes by the formula $\frac{1}{p} - \frac{1}{p'} = \frac{2}{\mathrm{R}}$ whence $\mathrm{R} = \frac{2pp'}{p'-p}$.

For example, let the focal length of the paraboloidal mirror P, Fig. 14, be ten feet; let $fc = p = 2$ ft. and $cm + mF = p' = 8$ ft. Here $\frac{p'}{p} = 4$; the image of the moon or other celestial object produced at F is therefore four times larger in diameter than it would be at f, the focus of the paraboloid; and $R = \frac{2pp'}{p'-p} = 64$ inches.

The method of testing the convex mirror while hyperbolizing it is shown in Fig. 15. The illuminated pinhole is placed very near the axis at F. The diverg-

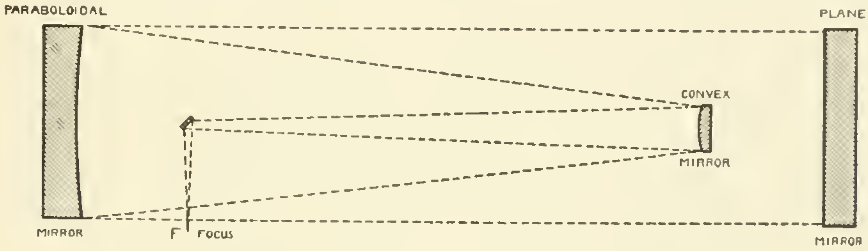


FIG. 15. DIAGRAM ILLUSTRATING TESTING OF HYPERBOLOIDAL MIRROR.

ing cone of light strikes the small plane mirror, then the convex, then the large paraboloid, whence if all of the mirrors are finished and are well adjusted or collimated, the light is reflected in a parallel beam to the large plane; returning, the rays are brought to a focus very near the axis of figure and in the plane of the illuminated pinhole. All of the mirrors except the convex one are silvered. The convex spherical surface with radius of curvature R, as above described, when viewed with the knife-edge test from the point F, presents the same general appearance of a smoothly curved surface of revolution, in strong light and shade, which a paraboloidal surface presents when similarly viewed from its center of curvature (see Fig. 8, p. 33). All that is necessary to produce the hyperboloidal surface is to soften down, with suitable polishing tools, the apparent broad protuberant zone between the center and edge, until the mirror, as seen from F, appears perfectly flat; *i. e.*, until the illuminated surface is seen to darken with absolute uniformity all over when the knife-edge is moved across the focus. This hyperbolizing may be done with small local or figuring tools, or with a full-size tool so trimmed as to give an excess of action on the broad zone a, or (what is usually best) by a combination of the use of both kinds of tools.

As in the case of the paraboloid, it is necessary in this test that all of the mirrors be lined up or collimated with care; otherwise the surface of the convex mirror will not appear as a surface of revolution, and cannot be properly tested. The axes of the paraboloid and hyperboloid must coincide, and the face of the large plane mirror must be at right angles to these axes. These adjustments are made by means of an extension of the method of collimation described in the preceding chapter, p. 35. First the paraboloidal mirror is adjusted so that its axis intersects the hyperboloid at its exact center or vertex; in making this adjustment fine threads are stretched diametrically across the cell of the convex mirror, this mirror being removed during this part of the adjustment. Next, the small diagonal plane is adjusted for inclination, care being taken that the intersection of the lines scratched in its film is placed in the axis of the paraboloid. Then the convex mirror is adjusted for inclination, by reflection. Finally, with the illuminated pin-hole in place, the large plane mirror is adjusted, as previously described.

CHAPTER XV.

SILVERING.

It is not my purpose to discuss the various processes of silvering. Several methods have been admirably described by Draper (see p. 2 of his book), by Brashear, and by Common (see p. 159 of his paper *On the Construction of a Five-Foot Reflecting Telescope*). I have used almost exclusively the formula published by Brashear in 1884, in which sugar is the reducing agent. After experience with this process, and when the grades of chemicals specified below are used, silver films are invariably obtained which take a perfectly black polish, and which are so thick as to be nearly opaque even to the sun's disk. Small mirrors are usually silvered face down; films which are satisfactory in all respects are obtained when this is done.

In the case of large mirrors it is more economical of silver, as well as safer and more convenient in manipulation, to silver face up. Two difficulties occur, however, when this is done; first, minute transparent spots are liable to occur in the film; these are so small, however, that they can be seen only when looking through the film at a bright object; second, the refuse silvering solutions must be poured off the mirror, after the silver has been deposited, at exactly the right stage of the reaction; if poured off too soon the film will be thin; if too late, the muddy-brown precipitate which settles upon the film will slightly tarnish the latter in such a manner that it will not take a perfect polish; it is only by experience that the optician is able to determine the right instant for pouring off the refuse solutions. Mr. Common encountered similar difficulties in silvering face up, and resorted to the use of solutions without caustic potash, and also to the use of Draper's method of reducing with Rochelle salt; these methods, while subject to their own special difficulties, do not give the objectionable precipitate. The writer has adhered to the use of a slight modification of Brashear's formula already mentioned, in part because no opportunity has occurred for comparing thoroughly the merits of the various formulæ, and in part because the films obtained by this method give entire satisfaction in use.

The Reducing Solution. This consists of distilled water, 200 parts; loaf-sugar or pure rock-candy, 20 parts; alcohol (pure) 20 parts; nitric acid (c. p.) 1 part. The proportions given are by weight. This solution is greatly improved by keeping, a solution which has been made for several months working more surely than one newly made. A gallon of this solution is usually made at one time.

The operation of silvering a 2-foot mirror face up will now be described. It will be assumed for the present that the back of the mirror is unsilvered. A silvering table is used, which is a strong structure of oak wood having a tilting frame carried on two trunnions, so that the mirror can be quickly turned from a horizontal to a vertical position, for the purpose of pouring off the cleaning and silvering solutions; a strong narrow edge-band of flexible steel prevents the mirror from sliding off; the tilting frame is heavily weighted below so that it cannot turn down accidentally. Thus all handling of the mirror while silvering is avoided.

The old silver film, if one exists, is removed with strong nitric acid on a bunch of absorbent cotton tied to a glass rod. The face and edge of the mirror are then quickly washed with distilled water. A band of strong brown drawing paper, which has been dipped in melted paraffin, is drawn around the edge of the glass and tightly bound to it by means of a thin band of copper with tightening screws; the paper should project about three inches above the glass; the joints should all be made water-tight by means of more paraffin and a warm iron. A dish about three inches deep is thus formed, with the mirror as its bottom.

A 10 per cent solution of pure caustic potash in distilled water is now used for thoroughly washing the face of the glass and the inside of the paraffin band; this is done with a large bunch of absorbent cotton tied to a glass rod. This solution is then poured out and the glass is similarly washed several times with fresh supplies of distilled water, to get rid of all traces of potash. Enough distilled water is now poured on the glass to entirely cover it while the silvering solutions are being mixed.

All of the vessels, graduates, etc., used for mixing the silvering solutions, must be thoroughly washed, first with nitric acid, then with caustic potash, and rinsed with distilled water, just as the mirror is cleaned.

For silvering the face of a 2-foot mirror, 2 ounces of silver nitrate (Powers & Weightman) are dissolved in 20 ounces of distilled water. One and one-third ounces of caustic potash, pure by alcohol (Merck), are dissolved in 20 ounces of water in a separate vessel, and the solution is cooled. Strong aqua ammonia (pure) is added, drop by drop, to the nitrate solution, while the liquid is thoroughly stirred; the mixture turns light-brown, then dark-brown; the ammonia is slowly added until the liquid becomes clear. The caustic potash solution is now added slowly, with thorough stirring; the mixture now becomes very dark-brown or black. Ammonia is again added, with thorough stirring, until the liquid again just clears. A solution of one-fourth ounce silver nitrate in 16 ounces of distilled water having been prepared, this is added to the mixture, a few drops at a time, with thorough stirring, until the entire solution has a decided straw color, while remaining transparent. This straw color is the test for the condition of instability which is absolutely necessary in order that the metallic silver shall be thrown out of combination when the reducing solution is added later. The solution is now thoroughly filtered through absorbent cotton.

A quantity of reducing solution is taken containing an amount of sugar equal in weight to one-half that of the entire amount of silver nitrate used; this is also filtered. The silver solution and reducing solution are now both diluted with distilled water, preparatory to mixing; the quantity of the diluted solutions, together, should be sufficient to cover the glass about one inch deep.

An assistant pours off the water which has stood on the glass, while the optician quickly mixes the dilute silver and reducing solutions in a large pitcher or granite-ware bucket. The glass being horizontal, the mixed solution is immediately poured on, and the mirror is rocked slightly by means of the tilting frame. The liquid quickly changes to a transparent light-brown color, then dark brown, then black, after which the silver immediately begins to deposit. The solution gradually changes to a muddy-brown color, and in three or four minutes after the solutions are poured on the glass, begins to clear; the light muddy-brown precipitate settling upon the film. With the proportions given, the silver film should be sufficiently thick in about five minutes after the solutions are poured on the glass provided that the room, glass, and solutions are all at a temperature of sixty-eight degrees or seventy degrees Fahrenheit. When first formed the brown precipitate is so light that it moves about with the rocking of the glass; but it very soon deposits in large areas on the film. As soon as this begins to occur, the solution must be very quickly poured off the glass, an abundance of distilled water poured on, and a large bunch of absorbent cotton, held in the fingers, instantly used to displace all streaks of the precipitate which adhere to the film. The film is now washed again and again with fresh distilled water and a soft bunch of cotton; then an abundance of water is poured on and the film allowed to soak for an hour. When this is poured off, the paper band is carefully removed, with the glass horizontal so that no liquid from the edge can run upon the silver film; this must be done quickly, before the latter has time to dry. A small amount of alcohol is now flowed on the film; this is repeated several times to get rid of all water; the glass is then turned on edge, and is quickly dried with a fan.

After standing for an hour or two in a dry room the film is to be burnished. A soft pad as large as the hand is made of the softest chamois skin; this is used on the film without rouge, with light circular strokes, to condense the silver. After two hours of this work a little of the finest washed dry *jeweler's* rouge is rubbed into the chamois-skin with a piece of clean absorbent cotton; from thirty to sixty minutes use of the pad with the same stroke as before should now bring the film to a perfect polish, without scratches.

If the back of the mirror is already silvered, the face can be silvered by the method just described, without injuring the film on the back; the mirror now rests upon three curved and beveled blocks of soft wood which touch only the rounded corner or edge of the back of the glass; extra precautions are now taken to prevent any of the solution from touching the back. I regard this method as much better in the case of large mirrors than to attempt to silver both back and face at the same time in a deep tray; in the latter method the difficulties of handling and properly cleaning the mirror are almost insurmountable.

The back of the mirror does not usually need silvering oftener than once in three or four years. The face is usually silvered two or three times a year, to keep it in the finest condition for photography, in which any yellowing of the film is very objectionable.

CHAPTER XVI.

A SUPPORT-SYSTEM FOR LARGE MIRRORS.

The proper support of mirrors in their cells when in use in the telescope is a matter of vital importance. Small mirrors can be made very thick and can be supported at their edges as a lens is supported; the cell must be so designed that no sensible change of position of the mirror in its cell can occur. The necessity of supporting large mirrors in such a manner as to prevent flexure from their own weight, in all positions which can occur in use, has long been recognized, and elaborate support-systems for this purpose have been devised and used by Rosse, Grubb, Common, and others. Comparatively little attention has been given, however, to two additional requirements which are no less important; first, the position of the mirrors in their cells should be defined with the greatest attainable stability, in order to secure permanence of adjustment or collimation; second, the method of support should be such that the silvered back of the mirror is exposed to the air as freely as possible. It is assumed that a large mirror need never be turned farther than ninety degrees from the position in which it lies horizontal upon its back.

In the *Astrophysical Journal* for February, 1897, the writer described a method of supporting large mirrors which fulfills all of the requirements named in the preceding paragraph. I have employed this method in the designs for the support-system of the 5-foot mirror. These designs are described and illustrated here.

I.—*The Back-Support.*

Let us consider the mirror to be divided into twelve imaginary segments of equal weight, as shown in Fig. 16, Plate VIII. The back of the mirror rests, primarily, upon three strong bronze plates, each ten inches in diameter, represented by the double circles *a* Fig. 16 and at *a* Fig. 17, the center of each plate being exactly behind the center of weight of the corresponding segments; these are called the stationary plates. The upper surface of each plate is flat and is ground to fit the flat back of the glass; the lower surface is spherical, and is ground to fit the large spherical socket in which it rests. It will be noticed that these plates are near the edge of the mirror, in the outer ring of segments; the base of stable support is therefore large. It is evident that by properly designing these plates and their supports we can fix with very great stability the plane of the mirror which rests directly upon them; there is no building out from the three primary points of support by means of intermediate levers and triangles, as in the older systems.

The weight of the remaining nine segments of the mirror is just balanced by means of nine weighted levers, each of which is entirely independent of every other, which lie in a plane parallel to the back of the mirror. One of these levers is shown in elevation at *c*, Fig. 17, and in plan in Fig. 21. The positions of the nine levers are indicated by dotted crosses in Figs. 16 and 18. These levers are suspended between pivots screwed through lugs connected to the cell. The cone bearings, shown in Fig. 21, are finely fitted, and are ground to reduce friction. The long arms of the levers carry adjustable lead weights (*d* Figs. 17 and 21) which are made in the form of plates, in order that they may occupy as little space as possible perpendicular to the plane of the mirror; the short arms of the levers are thus made to press against the backs of the corresponding segments through the medium of light plates of bronze represented by the single circles *b* Fig. 16 and at *b* Figs. 17 and 21.

The large mirror weighs very nearly 2000 pounds, so that each segment weighs $166\frac{2}{3}$ pounds. With the cell in a horizontal position the lead weight on each arm is adjusted until it just balances a standard weight of $166\frac{2}{3}$ pounds placed upon the plate on the short arm. This adjustment being completed the mirror is laid upon the support-system; three-quarters of its weight is carried by the nine levers, leaving one quarter to be divided equally between the three heavy plates *a*. Thus each of the twelve segments is entirely supported at the back, independently of all of the other segments. Now suppose that the edge-support, which will be described below, be introduced, and the entire system, with the glass, inclined in any direction and at any angle; all of the levers and weights retain the same position as before with reference to the glass, but they do not exert the same pressure, on account of the inclination; so far as the back-support is concerned there will still be a perfect balance maintained in the case of each segment; this is true whatever point of the edge of the mirror becomes lowest—*i. e.*, in whatever direction the levers lie with respect to the vertical plane through the axis of figure of the mirror.

It should be noticed that in the case of each of the twelve 10-inch supporting plates only a ring one inch wide around the edge is in contact with the glass; the part of each plate inside of this ring consists of deep, narrow arms, which do not touch the glass, and which allows free access of air to the latter.

For very large or thin mirrors a larger number of plates and levers can of course be used. An incidental advantage which occurs when this is done is that the base of stable support afforded by the three stationary plates is still larger, compared with the size of the mirror, than when twelve plates are used.

II.—*The Edge-Support.*

The relation between the back-support and edge-support is so intimate that any inefficiency in the latter must injuriously affect the operation of the former, however perfect that may be in itself. In an equatorial reflecting telescope, different parts of the edge of the mirror become successively lowest, as the position of the telescope changes. With the flexible band and cushioned edge-support so much used in the past, the heavy mirror necessarily changes its position, laterally, with

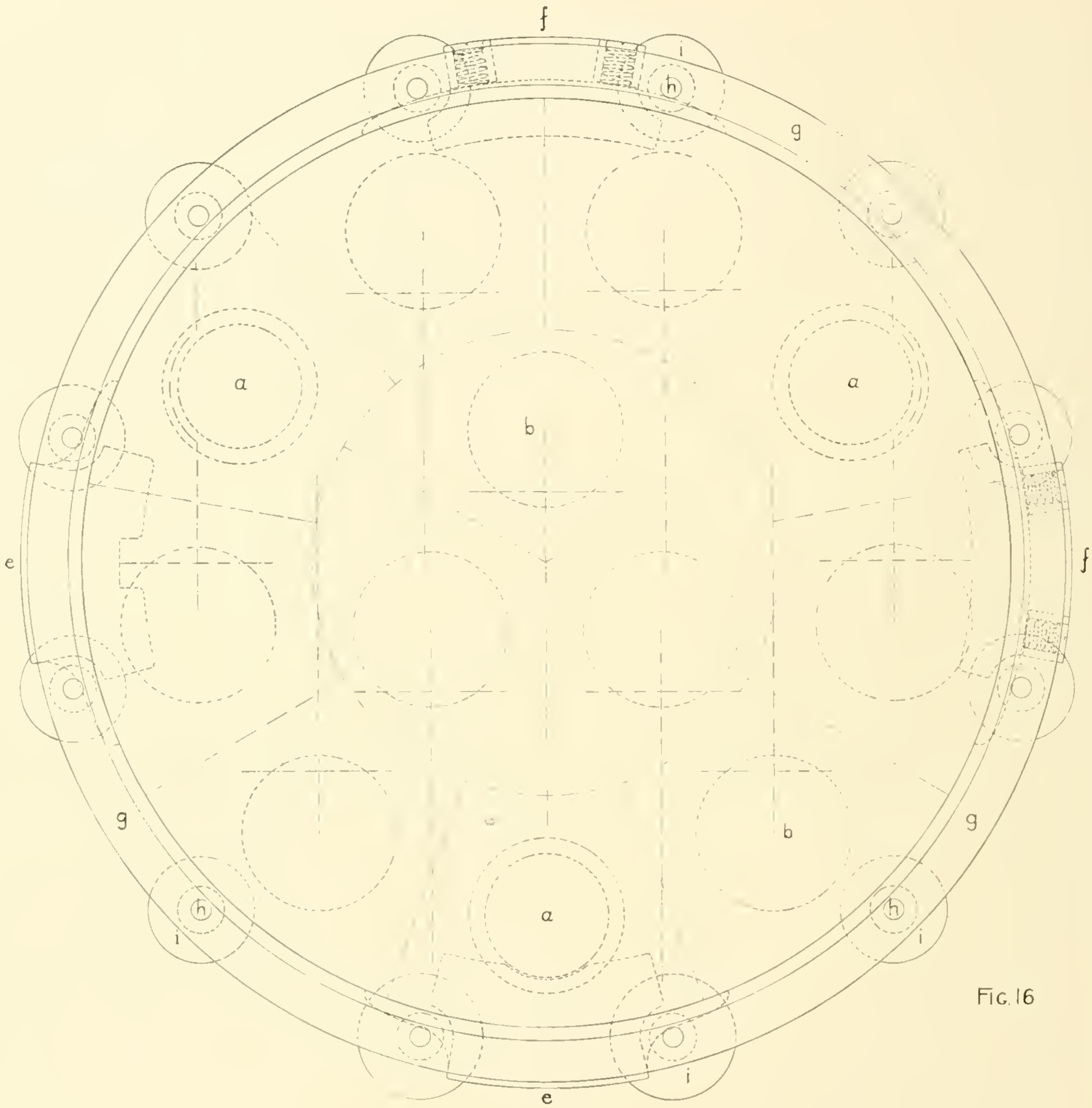


Fig. 16

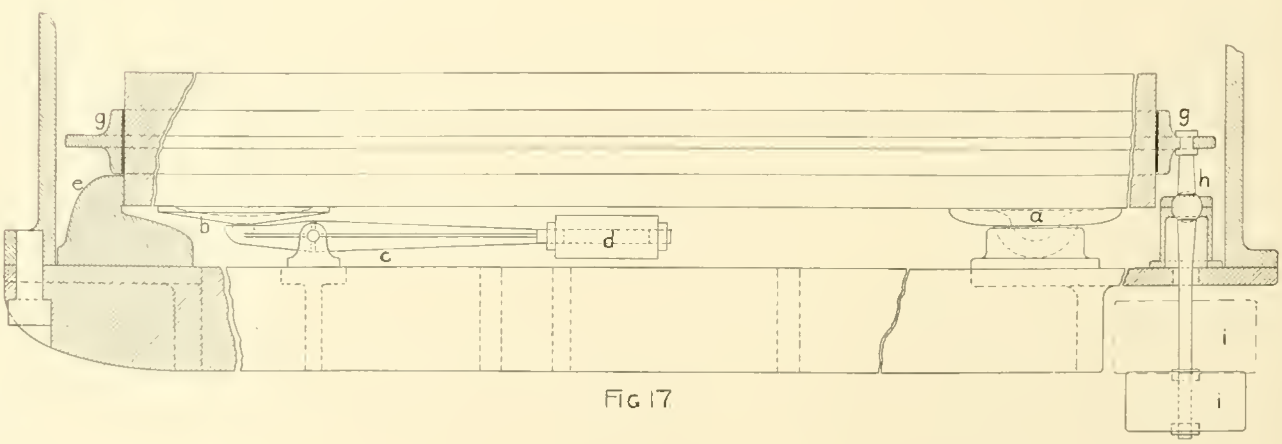
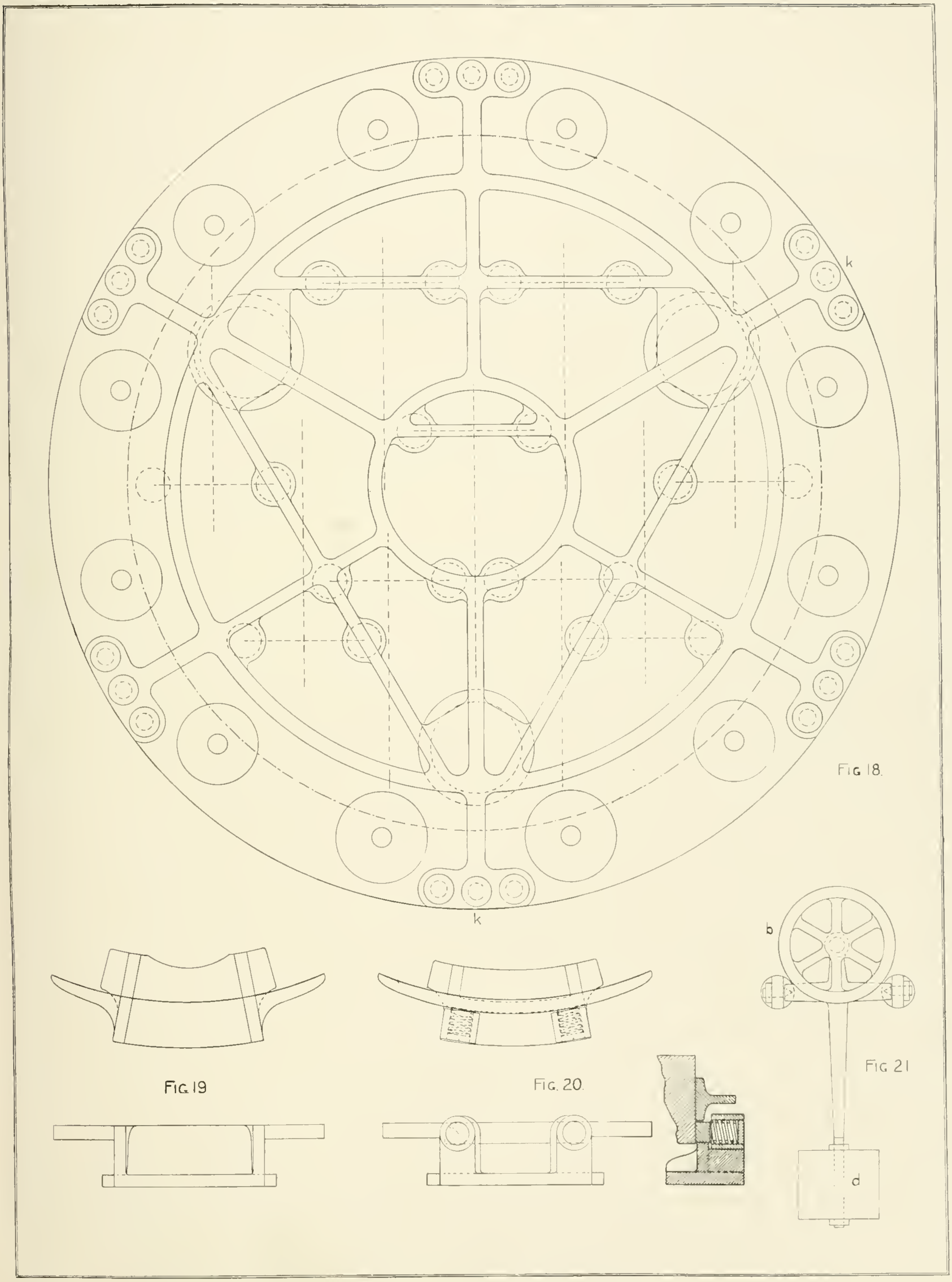


Fig 17

SUPPORT SYSTEM FOR LARGE MIRROR.



SUPPORT SYSTEM FOR LARGE MIRROR.

respect to its cell, in taking its position down against the edge-support; thus not only is permanence of position lost, but this tendency to lateral shift must impair the freedom of operation of the back-support system.

In the present plan four metal arcs are used which rigorously define the position of the mirror laterally. Two of these arcs (*e* Figs. 16 and 17, and Fig. 19), adjacent to each other, are bolted down to the cell, and their inner edges are scraped to fit the ground edge of the glass; these are called the stationary arcs; the other two arcs (*f* Fig. 16 and Fig. 20), diametrically opposite the stationary ones, exert a slight pressure against the edge of the mirror, by means of springs, for the purpose of seating the mirror against the stationary arcs and holding it there; this pressure need amount to only a very small percentage of the mirror's weight, for all of the lateral pressure due to the weight of the mirror when the latter is inclined is carried by a strong metal *counterpoising ring* of T section (*g* Figs. 16 and 17); this completely encircles the edge of the mirror, and fits it loosely, a band of leather or thick felt paper being inserted between the ring and the glass. For convenience in description, imagine this ring to be suspended from the tube above, by means of three short wires, so that if the mirror were removed the ring could swing freely in its own plane. The ring is pressed up against the edge of the mirror, when the latter is inclined, by a system of twelve short weighted levers (*h* Figs. 16 and 17) which hang perpendicular to the plane of the ring. These levers are suspended from the cell-plate behind the ring, by means of ball-and-socket joints, as shown in Fig. 17, or preferably, to reduce friction, on pivoted universal or Hooke's joints. The ends of the short upper arms of these levers fit loosely into holes in the ring; the long lower arms carry lead weights (*i* Figs. 16 and 17) which are capable of slight adjustment.

Assuming that the counterpoising ring weighs 400 pounds, so that the combined weight of ring and mirror is 2400 pounds, the adjustment of the edge-support levers is effected by turning the entire cell to a vertical plane, with the mirror and ring removed, and adjusting each of the twelve lead weights until it just balances a standard weight of 200 pounds hung on the short arm of the lever at the point where this is to touch the ring.

I regard the use of a support-system which will fulfill all of the conditions mentioned at the beginning of this chapter as absolutely essential for large mirrors. Only those who have tested large mirrors and combinations of mirrors in the optical shop, and those who have actually used large reflecting telescopes, can fully appreciate the necessity of a support-system which will both support the mirrors without constraint and flexure, and define their positions permanently with respect to the tube and axes, in all positions of the telescope. These conditions can now be attained easily and economically; without them it is folly on the one hand to expect good definition and successful photographs, or, on the other hand, to complain that the reflecting telescope is subject to serious inherent difficulties which cannot be overcome. In the case of large mirrors in which the ratio of thickness to diameter is not less than as 1 to 9 or 1 to 10 the support-system just described floats the mirror so perfectly in all positions which can occur in actual use that no flexure or distortion can be detected with the most sensitive optical tests. Furthermore, with the method of edge-support described, and in the case of the 5-foot mirror weighing a ton, no lateral shift amounting to $\frac{1}{2000}$ inch can occur when the mirror is turned in extreme oblique positions.

In Figs. 17 and 18 is shown the massive cell-plate of cast-iron which carries the mirror and its support-system, and which is connected to the short cast-iron section of the tube; this connection is made by means of strong adjusting screws, by means of which the mirror and its support-system, as a whole, are adjusted for collimating the mirror; these adjusting screws are shown at *k*, Fig. 18. Additional screws are also shown at *l* in this figure; these are backed out of the way when collimating is being done; when this is finished they are brought into position, and assist in bolting the cell-plate rigidly to the tube. As is shown in Figs. 17 and 18, the central part of the cell-plate, a circle about 50 inches in diameter, consists of open ribs or arms which allow free access of air to the silvered back of the mirror.

When the face of the mirror is to be resilvered, the cell-plate, support-system, and mirror are removed as a whole, and silvering is done in the manner described in the preceding chapter, without taking the mirror from its supports or disturbing the adjustments of the latter in any way. Furthermore, the mirror can be taken out of the telescope in this way, silvered, and replaced, without sensibly disturbing its collimation or the position of the focal plane. When the back of the mirror must be resilvered, which need not be done oftener than once in three or four years, the glass must of course be removed from its support-system.

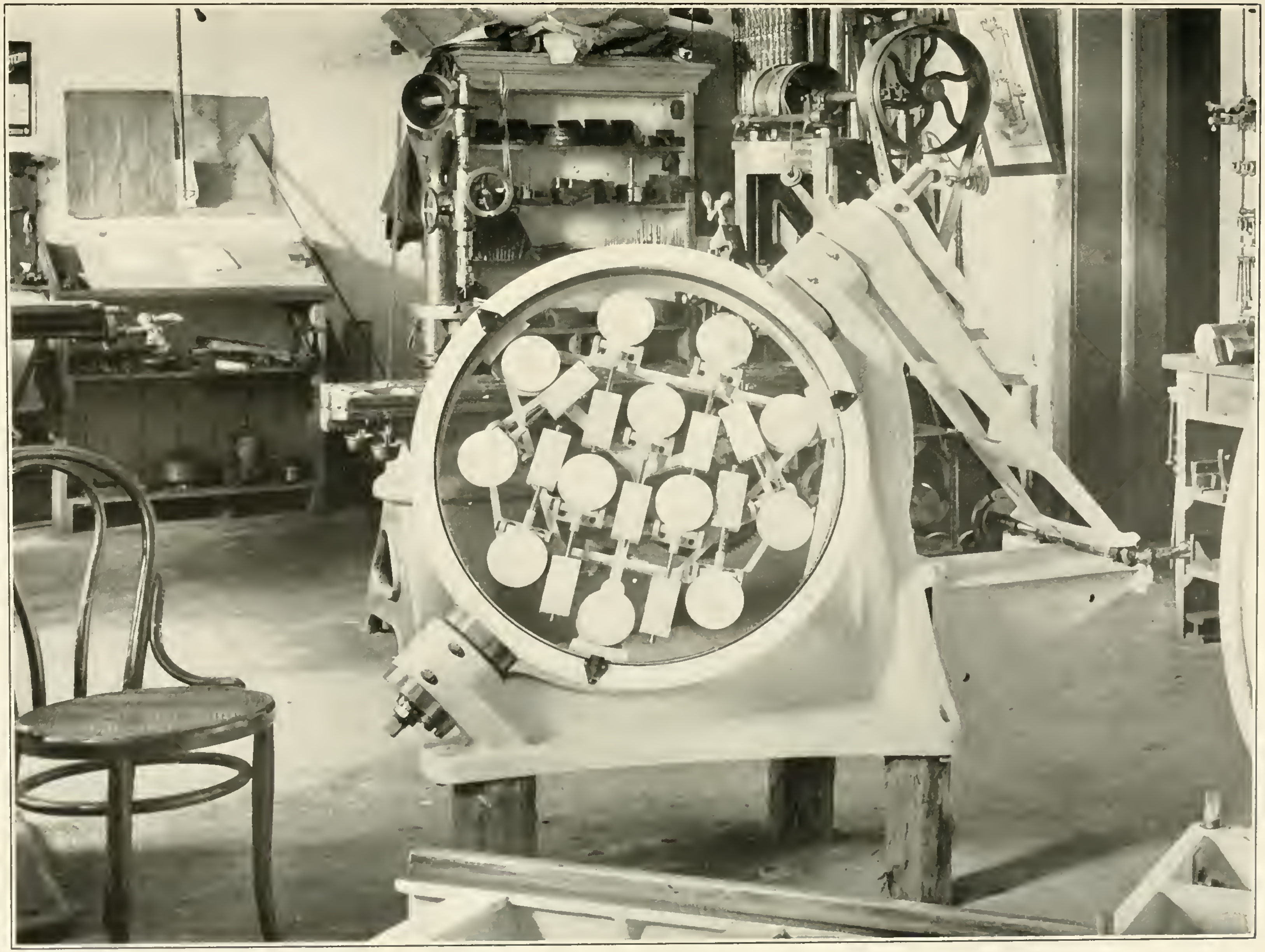
This support-system, as described, may appear complicated and expensive; in reality it is not so, for all of the levers, plates, etc., used for the back-support can be exactly alike, as can also the levers used for edge-support; even when a greater number of levers than twelve are used the construction is simple and economical.

In Plate x is shown a 30-inch plane mirror supported at the back by twelve plates and nine levers as described above; the mirror is shown unsilvered, so that the plates are seen through 4 inches of glass. This is a part of the 30-inch cœlostat recently constructed from the writer's designs in the instrument and optical shops of the Yerkes Observatory.

CHAPTER XVII.

A MOUNTING FOR A LARGE REFLECTING TELESCOPE.

In considering the requirements for a modern reflector mounting for photographic and spectroscopic work, the writer can probably not do better than to describe the designs for the proposed mounting of the 5-foot reflector. These designs are the result of experience both in optical work and in the use of the 2-foot reflector and the 40-inch refractor of the Yerkes observatory in astronomical photography.



LARGE COELOSTAT WITH 30-INCH PLANE MIRROR.

PLATES AND LEVERS FOR BACK-SUPPORT ARE SEEN THROUGH THE UNSILVERED GLASS.

With the present great improvements in the materials and methods of machine construction there is no longer any excuse for unstable and inconvenient mountings for reflectors. The focal length of modern reflectors intended for photography is short; the ratio of aperture to focal length generally used in such instruments will probably be not greater than as 1 to 4, nor less than as 1 to 6; with such ratios the mounting can be made extremely compact and rigid. By the addition of a small convex mirror the equivalent focal length can be increased from three and one-half to five times, and fine definition retained; when this is done the actual length of the tube is less than when the telescope is used at the primary focus.

The reflecting telescope defines well only at or near the optical axis; hence the mirrors must remain in perfect adjustment with reference to each other and to the eyepiece or photographic plate, in all positions of the telescope which can occur in use. Not only must the mirror supports be such as to define the position of the mirrors rigorously always, as described in the preceding chapter, but the short tube must be excessively strong and rigid so that no sensible flexure can occur. This is especially necessary when the telescope is used as a Cassegrain, or as a *coude*; for when these forms are employed it is only when the axes of the paraboloid and hyperboloid coincide that fine definition can be secured. When the necessity of these conditions is fully realized by makers and users of reflectors, a marked advance in the usefulness of reflecting telescopes will result. It was the lack of such rigidity and of such permanence of adjustments, fully as much as the lack of means of rigorously testing the optical surfaces, which made the old Cassegrain reflectors, including the great Melbourne instrument, such lamentable failures. I consider the failure of the Melbourne reflector to have been one of the greatest calamities in the history of instrumental astronomy; for by destroying confidence in the usefulness of great reflecting telescopes, it has hindered the development of this type of instrument, so wonderfully efficient in photographic and spectroscopic work, for nearly a third of a century.

When the telescope is to be used for photography, either direct or spectroscopic, it is indispensable that the mounting be so designed that reversal is not necessary when passing the meridian; for it is frequently necessary to expose for six or eight hours without reversal, on faint objects; and the best part of such an exposure is that in which the celestial object is near the meridian. Several forms of reflector mounting have been devised in which reversal is not necessary; the well-known English closed-fork mounting is one of them.

In designing the proposed mounting of the 5-foot reflector of the Yerkes Observatory, of twenty-five feet focal length, the writer has adopted the form in which a short open fork is used at the upper end of the polar axis. The tube hangs between the arms of this fork, being carried on two massive trunnions; the heavy lower end of the tube is so short that it can swing through, between the arms of the fork, for motion in declination.

The fork mounting presents several marked advantages with respect to compactness and stability, as well as convenience and economy, over all forms which are modifications of the German equatorial mounting, in which the tube is carried out at one side of the equatorial head. The tube, carrying the great weight of the mirror and its cell, is here supported at two opposite sides, instead of from one side only, as in the German forms; no heavy counterpoises are required; this form is much better adapted for the *coude* arrangement of mirrors, so essential in work with very large spectroscopes, only three reflections in all being necessary for this arrangement; furthermore, when the instrument is used at the primary focus, the upper end of the tube is more easily accessible, in all positions of the instrument, from an observing carriage attached to the inside of the dome.

The weight of the moving parts of the telescope will be about twenty tons. On account of this great weight, and also of the overhang of the fork above the bearings of the polar axis, an efficient anti-friction apparatus for the polar axis is demanded, which will at the same time relieve the effect of the overhanging weight of the upper end of the polar axis. The advantages afforded for this purpose by mercury flotation, when this is properly applied, are so great, and the mechanical details for such flotation work out so simply and economically, that this method will undoubtedly be used.

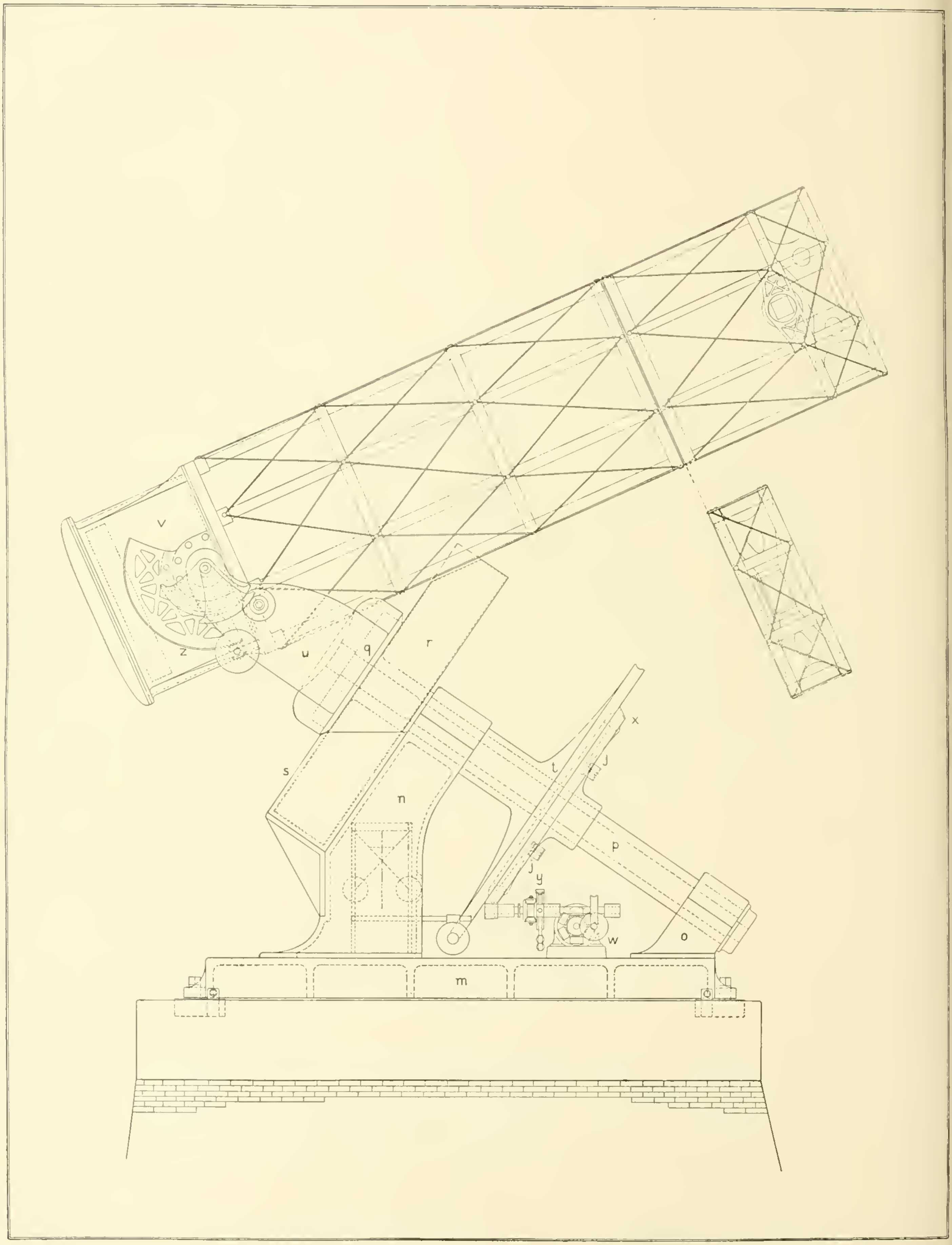
The proposed mounting will now be briefly described in detail, and attention will be called to many points which are indispensable to the success of a reflecting telescope to be used for photography.

The equatorial head consists of three iron castings, the triangular base-plate *m*, Plate XI, and the two posts *n* and *o*, which carry the bearings for the polar axis. Both posts are hollow, with walls $1\frac{3}{4}$ inch thick, and are bolted and pinned to the base casting; the post *n* contains the large driving clock.

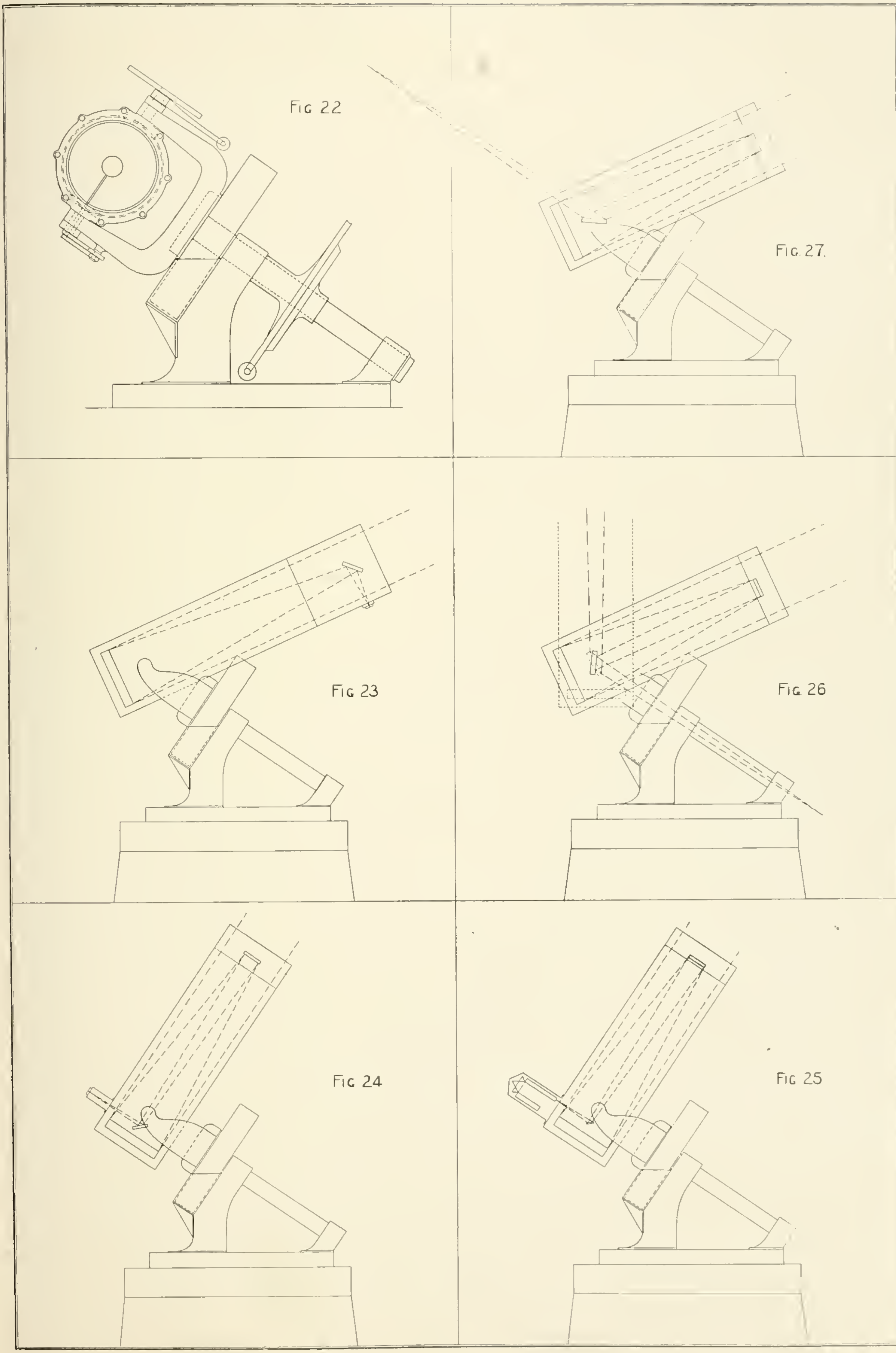
The polar axis *p* is of hydraulic-forged steel, with a head or flange *q*, 48 inches in diameter and 7 inches thick, forged upon it; the axis is $14\frac{1}{3}$ feet long over all, is 20 inches in diameter for a distance of 2 feet below the head, and is 16 inches in diameter for the remaining $11\frac{2}{3}$ feet of its length; the axis is hollow, with walls $4\frac{1}{2}$ inches thick. The bearings of the polar axis are of hard Babbitt metal, and are halved.

Attached to the lower surface of the 4-foot head of the polar axis is the large hollow disk or float *r*, 10 feet in diameter and $22\frac{1}{2}$ inches thick or deep; this is constructed very strongly of angle steel covered with steel plates $\frac{3}{8}$ inch thick; the whole is finished smooth on the outside, and is turned true in a lathe. The corresponding trough *s* is of cast-iron and is turned true on the inside. The inner surface of the trough is separated by $\frac{1}{8}$ inch all around from the outer surface of the float; this space is filled with mercury. With the dimensions given the immersed part of the float displaces about 45 cubic feet of mercury, which thus floats about nineteen tons, or 95 per cent of the weight of the moving parts of the telescope. The center of flotation is vertically below the center of weight of the moving parts. Only three-quarters of a cubic foot of mercury is required to float nineteen tons in this manner.

The importance in astronomical photography of the smoothness of motion afforded by really efficient flotation of the moving parts cannot be overestimated. The great size of the worm-wheel *t* which rotates the polar axis, will materially



DESIGN FOR MOUNTING OF FIVE-FOOT REFLECTING TELESCOPE.



DESIGN FOR MOUNTING OF FIVE-FOOT REFLECTING TELESCOPE.

assist in giving smoothness and accuracy of driving; this worm-wheel is 10 feet in diameter.

Attached to the upper surface of the 4-foot head of the polar axis, by means of a circle of 2-inch bolts, is the large cast-iron fork *u*, different views of which are shown in Plate XI and Fig. 22, Plate XII. The extreme outside width of this fork is $8\frac{1}{3}$ feet; it is of hollow or box section, with walls averaging $1\frac{1}{2}$ inches thick; it weighs about five tons.

Between the two arms of the fork hangs the short round cast-iron section *v* of the tube; two 7-inch steel trunnions, having large heads or flanges, are bolted to this casting, and turn in bronze bearings at the upper ends of the fork arms; this part of the tube is 46 inches long; its inside diameter is 70 inches; its thickness is 1 inch; it is reinforced at top and bottom by flanges. To the lower flange is connected the cell-plate (described in the preceding chapter) which carries the large mirror and its support-system.

To the upper flange of the short cast-iron section of the tube is bolted a strong cast-iron ring which forms the lower end of the main or permanent section of the octagonal skeleton tube; this section is 13 feet 11 inches long, and 6 feet 8 inches outside (diagonal) diameter. It is constructed of eight 4-inch steel tubes, connected by strong rings designed to resist compression; diagonal braces, which are connected together at all intersections, greatly increase the rigidity of the structure. This entire section is so rigid that it can be placed in a large lathe for facing the ends parallel to each other, and for turning a slight recess in the ends for the purpose of accurately centering the parts which are to be connected to them.

To the upper end of the permanent section of the skeleton tube can be attached any one of three short extension tubes or frames, as desired; two of these are shown in Plate XI. The lower end of each extension is turned true, with a projecting ring which fits into the turned recess in the upper end of the permanent section. With this arrangement the various extensions can be removed and replaced without sensibly affecting the adjustments of the mirrors and other apparatus which they carry, with reference to the optical axis of the large mirror.

The extension which is shown in place on the telescope in Plate XI and in Fig. 23, Plate XII, is the longest one; it is 6 feet 11 inches long; it is used for all work at the primary focus of the telescope; it carries the diagonal plane mirror and its supports, and the eyepiece and double-slide plate-carrier. This extension can be rotated upon the turned end of the permanent section, so that the eyepiece or photographic apparatus can be brought to the side of the tube which is most convenient for observing or photographing a given object. The diagonal plane mirror is of the finest optical glass, is elliptical in outline, is 15 x 22 inches in size, and is $3\frac{1}{2}$ inches thick; it is carried in a strong cast-iron cell, which is supported from the skeleton tube by four thin steel plates, as shown in Plate XI. The diagonal plane mirror is sufficiently large to fully illuminate a field 7 inches in diameter at the primary focus. The double-slide plate-carrier is designed for $6\frac{1}{2}$ x $8\frac{1}{2}$ inch photographic plates.

The other two extensions of the tube, which are only about 2 feet long, are employed when the telescope is used as a Cassegrain and as a *coude* respectively; each carries a convex mirror 19 inches in diameter and $3\frac{1}{6}$ inches thick, of the finest optical glass, and of the proper curvature for the purpose desired.

Figs. 24 and 25, Plate XII, show the telescope used as a Cassegrain. In these cases the amount of amplification introduced by the convex mirror is about $3\frac{1}{2}$ diameters (see p. 38); the equivalent focal length is therefore about $87\frac{1}{2}$ feet, and the ratio of aperture to focal length as 1 to $17\frac{1}{2}$. Fig. 24 shows the telescope as used for direct photography with the double-slide plate-carrier at the secondary focus. In Fig. 25 a spectrograph similar to the large Bruce spectrograph of the Yerkes Observatory is shown attached to the north side of the short cast-iron section of the tube; this affords a most stable base of support for the spectrograph, at a point where it can be easily counterpoised.

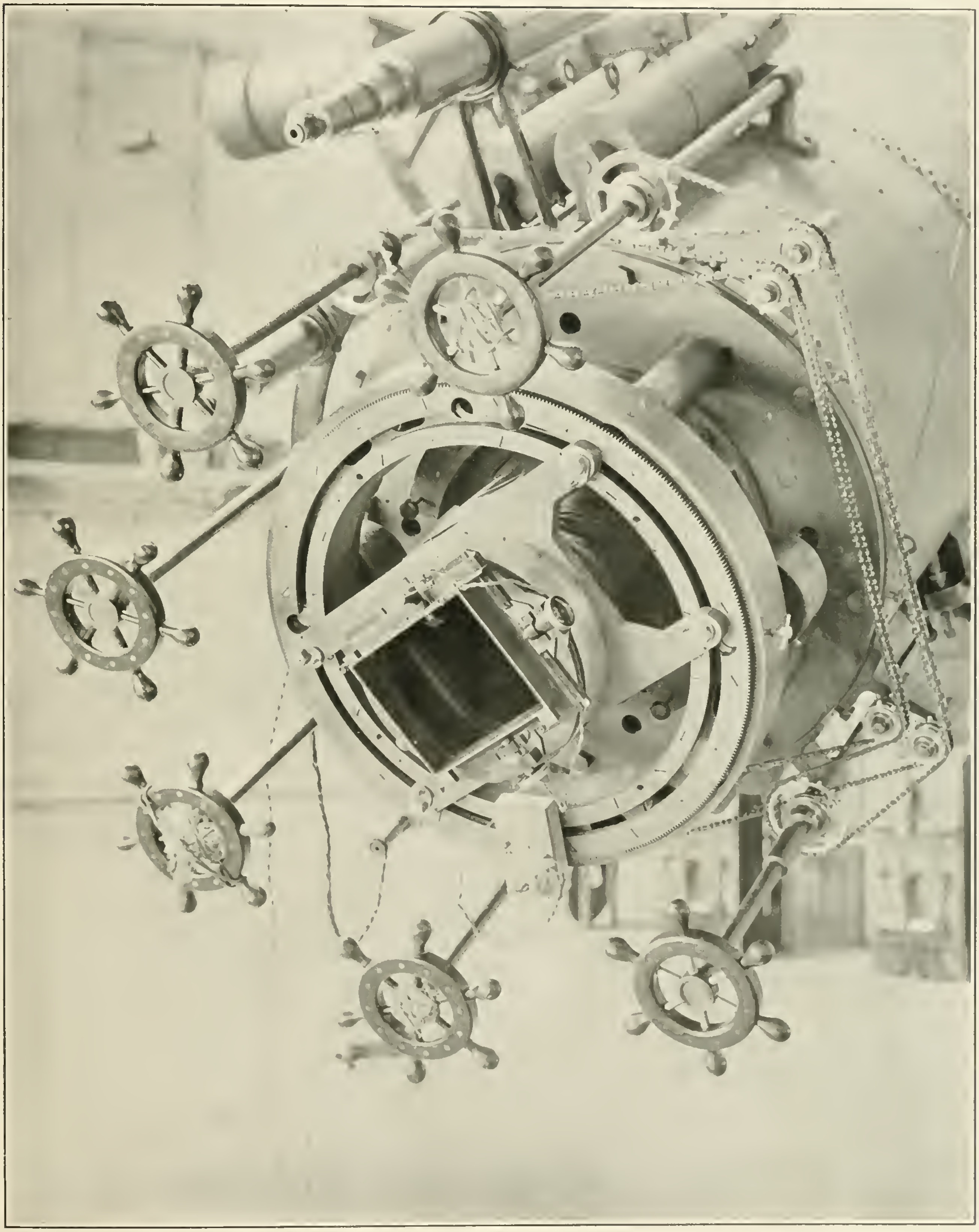
Figs. 26 and 27, Plate XII, illustrate the use of the telescope as a *coude;* the curvature of the convex mirror is now such that the equivalent focal length is about 125 feet. The cone of rays from the convex mirror strikes a diagonal plane mirror at the intersection of the polar and declination axes, and is by it reflected *in a constant direction*, which can be toward either the north or south pole of the heavens, as desired. This arrangement is almost indispensable when extremely large and powerful spectroscopes and other kinds of physical apparatus are to be used with the telescope; the focus is now in a constant position, so that such instruments need not be attached to the telescope, but can be mounted on stationary piers, in constant temperature rooms, if desired.

A brief description of the mechanism for quick-motion and slow-motion in right ascension and declination should be given. These are planned to be entirely electrical, although hand-motions are added, to be used in case of an emergency. Quick-motion in right ascension, both east and west, is given by the reversible motor w; this is connected by gearing to the large bevel-gear x through the medium of an electric clutch y. The bevel-gear x is permanently fixed to the polar axis. When the switch which starts the motor is thrown in, the electric clutch y acts, and a motion of rotation is communicated to the polar axis; this rotation is only at the rate of 45 degrees per minute; this is sufficient, since reversal is never necessary; hence very little power is required. The clutch is so adjusted that it will slip when even slight undue resistance is encountered. When the current is shut off from the motor the clutch is released automatically; the polar axis is then free from the motor and gear-train.

Quick-motion in declination is given in a manner entirely similar to that in right ascension, by a small reversible motor attached directly to the large cast-iron fork; this motor drives, through the media of a gear-train and an electric clutch, the toothed sector z, which is permanently fixed to the cast-iron section of the tube.

The driving-clock and 10-foot worm-wheel are "clamped in" to the polar axis, when desired, by the electric clamps j which lock the 10-foot worm-wheel to the bevel-gear x: the former is of course free to turn on the polar axis when not thus clamped.

Slow-motion in right ascension is given by means of a small reversible motor



LARGE DOUBLE-SLIDE PLATE-CARRIER ATTACHED TO 40-INCH REFRACTOR; YERKES OBSERVATORY.

which acts on a set of differential gears in the shafting connecting the driving-clock and the driving-worm. This device is used on the 2-foot reflector and on the 30-inch cœlostat, and is extremely simple and effective.

Slow-motion in declination is given by means of a small reversible motor which acts on the long sector attached to the upper trunnion shown in Fig. 22, Plate XII.

In concluding this necessarily brief and incomplete description of a modern reflector mounting, attention should be called to an attachment which is absolutely indispensable for the best results in direct photography of all celestial objects requiring long exposure. I refer to the double-slide plate-carrier, by means of which hand-guiding or correcting for the incessant small irregular movements of the image, which are nearly always visible in large telescopes, can be done incomparably more accurately and quickly than by any other means now known. This device is due to Dr. Common, who described it in *Monthly Notices*, Vol. 49, p. 297. In 1900 the writer designed and constructed a small attachment of this kind for use with the 40-inch refractor and the 2-foot reflector; this attachment and its use are described in the *Astrophysical Journal* for December 1900, p. 355.

The photograph of the central parts of the Andromeda Nebula (Plate I), was made by the writer with this small plate-carrier attached to the 2-foot reflector. The exposure time in this case was four hours. The images of the fainter stars on the original negative are only 2 seconds of arc in diameter; stars are shown which are more than a magnitude fainter than the faintest stars which can be detected visually with the 40-inch refractor; intricate structure and details are shown in the nebulosity, which are entirely invisible with the 40-inch refractor and all other visual instruments, and which have never been photographed before. When it is remembered that the focal length of the 2-foot reflector is only 93 inches, and that the aperture was in this case reduced to 18 inches, in order to secure a larger field than is well covered when the full aperture is used, some idea can be gained of the results which could now be obtained in celestial photography with a modern reflecting telescope which would compare in size, cost, and refinement of workmanship with the great modern refractors.

In Plate XIII is shown the large double-slide plate-carrier, taking 8 x 10 inch plates, which was constructed from the writer's designs in 1901, for use with the 40-inch refractor; the plate-carrier is here shown connected to the eye-end of the great telescope. A description of this attachment, together with some photographs obtained with it, will be found in the *Publications of the Yerkes Observatory*, Vol. II, p. 389.

SMITHSONIAN CONTRIBUTIONS TO KNOWLEDGE
PART OF VOLUME XXXIV

Hodgkins Fund

A CONTINUOUS RECORD OF ATMOSPHERIC NUCLEATION

BY

CARL BARUS
HAZARD PROFESSOR OF PHYSICS IN BROWN UNIVERSITY, PROVIDENCE, R. I.

(No. 1651)

CITY OF WASHINGTON
PUBLISHED BY THE SMITHSONIAN INSTITUTION
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The Knickerbocker Press, New York

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Commission to whom this memoir has been referred:

WILDER D. BANCROFT.

EDGAR F. SMITH.

ADVERTISEMENT.

In the present memoir, entitled "A Continuous Record of Atmospheric Nucleation," the author further discusses his researches on the nucleus, as published in *Experiments with Ionized Air*, *Smithsonian Contributions to Knowledge*, vol. XXIX, 1901, and in *Structure of the Nucleus*, issued as part of the same volume in 1903. The investigation has been carried on with the aid of a grant from the Hodgkins Fund of the Smithsonian Institution.

Doctor Barus describes the nucleus as a dust particle small enough to float in the air, but larger than the order of molecular size. Such a particle precipitates condensation in an atmosphere saturated with water vapor in its immediate vicinity. When these nuclei occur approximately of uniform size in thousands and millions, they give rise to condensational phenomena of transcendent beauty and importance. By far the greater number of nuclei are initially ionized, or at least carry electric charge.

In addition to mechanical, thermal, and chemical processes, high potential is shown to be a fruitful source of nuclei. Certain kinds of radiation, like ultraviolet light, or the X-rays, or radioactive bodies, may also generate nuclei in the dust-free air through which the radiation passes.

The term "nucleation" is here used to denote the number of nuclei per cubic centimeter regardless of their source or special properties.

The scope of the present memoir is summarized by the author in his preface.

In accordance with the rule adopted by the Smithsonian Institution, the manuscript has been submitted for examination to a Committee consisting of Professor Wilder D. Bancroft, of Cornell University, and Professor Edgar F. Smith, of the University of Pennsylvania, and, having been recommended for publication, it is herewith presented in the series of *Contributions to Knowledge*.

S. P. LANGLEY,
SECRETARY.

Smithsonian Institution,
Washington, May, 1905.

PREFACE.

"What is a nucleus?" asks my friend, smiling incredulously. The conviction has become prevalent that only the ions induce condensation, and my own consistent adhesion to the nucleus since my report to the U. S. Weather Bureau (Bull. 12) in 1893 is often looked upon as heretical obstinacy. But this is quite unjust, unjust even to those who have with such brilliancy maintained the occurrence of condensation in ions. The nucleus has not left the field in discomfiture. It has merely been forced reluctantly and under conditions of extreme supersaturation to share its functions in this respect with the ubiquitous and irrepressible ion.

But to reply: The nucleus is at the outset simply a dust particle, small enough to float in the air, but much larger than the order of molecular size. Such a particle precipitates condensation in an atmosphere supersaturated with water vapor in its immediate vicinity, for the reasons long ago (1880) pointed out by Lord Kelvin in his brief but epoch-making paper. The support of this explanation was established experimentally by Coulier (1875), Kiessling (1884 *et seq.*), von Helmholtz (1886, 1887), and others, and, with particular ingenuity and breadth of view, by John Aitken (1880, particularly 1888 *et seq.*)

A single nucleus, however, would be of but little interest. It is when the nuclei occur approximately of uniform size in thousands and millions that they give rise to condensational phenomena of transcendent beauty and importance. To produce these legions of nuclei is not impossible by mechanical means, just as we can, for instance, triturate a solid to a remarkable degree of fineness; but the impalpable powders are perhaps best produced by chemical or at least by very refined physical processes. Similarly, though a class of interesting nuclei may be produced by vigorously shaking liquids, or, better, by mutually impinging jets or by jets impinging on a solid obstacle, nuclei are more abundantly produced by ignition or combustion. Such ignition, moreover, should be unaccompanied by any kind of smoke, as the gross particles in this case are an efficient means of absorbing nuclei. A clear non-luminous bunsen flame, a red-hot metal or any other solid, like glass, for instance, is a powerful nucleator. It is not even necessary that the solid be red-hot. Phosphorus is subject to a peculiar kind of chemical reaction, whereby nuclei are produced at 13° or a little below, and are then produced from the smokeless body in maximum abundance. Fuming phosphorus is a relatively weaker nucleator. Many gaseous sulphides, on mixture with air, become good nucleators. Even dust-free coal gas and dust-free air, on commingling, set free nuclei.

Certain hygroscopic liquids like concentrated sulphuric acid are remarkable nucleators. They probably make up a class by themselves. At least it is not improbable that 1,000 or 1,000,000 molecules per cubic centimeter may escape from such a body by ordinary evaporation, in spite of the low vapor pressure. Since each such molecule is hygroscopic, stable nuclei may be formed in a saturated atmosphere by condensation of the water vapor. Sulphide and sulphur nuclei are in turn probably oxydized to sulphuric acid.

In addition to mechanical, thermal, and chemical processes, high potential is a fruitful source of nuclei. A metal highly charged with electricity, or even a glass insulator, or the nodal points in the metallic pathway of a stationary electric wave are a source of nuclei. There is probably always an electric glow present in such cases, though there need be no spark.

Finally (and here we reach debatable ground), certain kinds of radiation, like ultra-violet light, or the X-rays, or radioactive bodies, generate nuclei in the dust-free air through which the radiation passes.

Air originally made quite dust-free by filtration or otherwise, if exposed to any of these sources becomes more or less filled with a freight of nuclei, fleeting or persistent, and we may for brevity introduce the term nucleation to denote the number of nuclei per cubic centimeter, regardless of kind or origin or other properties possessed, and considered solely with respect to their tendency to promote the condensation of water vapor in supersaturated moist air. If the supersaturation is sufficiently pronounced the air molecules in successively greater numbers as the supersaturation increases must themselves become nuclei, probably beginning with the more complex systems. This, for instance, occurs in the blues, opaques, and the succeeding browns and yellows of the first order of the axial colors of the steam jet. The importance of experiments in the spontaneous condensation of dust-free moist air was pointed out in my report to the Weather Bureau in 1893, p. 48 *et seq.;* they were first carried out in an independent manner and with exquisite finish by C. T. R. Wilson (1897).

The nucleus as an inert excessively small body, just transcending the order of molecular dimensions, and occurring in immense numbers, has an interest of its own; but this interest becomes much enhanced when it is found that by far the greater number of nuclei are initially ionized, or at least carry electric charge. The cases in which this does not occur are sufficiently exceptional to prove the rule, though such nuclei need not for this reason be less efficient. They probably admit of a categorical classification, such as has been suggested above for concentrated sulphuric acid and sulphides. Apart from these, all nuclei produced by ignition, by high potential, by the X-rays, or by radiation are powerfully ionized. So marked is the quality that certain investigators (in particular the younger von Helmholtz, 1887) have endeavored to find in the ionization a sufficient cause for the condensation of supersaturated moist air, or at least an additional tendency to promote it. J. J. Thomson (1888) was the first to adduce theoretical reasons for the suspected condensational activity of the ion. In the time since, so large in number and so important have been the researches in which the precipitation of supersaturated water vapor on ions enters as an argumentative premise, that insistence on the functions of the nucleus has dwindled by comparison. I must nevertheless claim the right of an independent investigator to interpret my work in a way which seems to me inevitable; and I have therefore ventured to believe that, so far as experimental evidence goes, the occurrence of electrical excitation is quite without influence in promoting condensation of moisture in supersaturated air. However ionization may be produced in the laboratory, whether by X-rays, or by ignition, or by high potential, by chemical means, or even by excessively vigorous trituration as in jets, it is always accompanied by nucleation. The average size of the nucleus resulting depends for a given medium on the time of exposure to the exciting cause and its intensity; or, in general, upon the number of nuclei produced per cubic centimeter per second. Roughly speaking, if the conditions producing ionization are sufficient and if they are maintained, there will be continuous growth in the number and size of the nuclei. On this question I have already expressed myself at some length in *Nature* (vol. LXIX, 1903, p. 103), believing that "out of all systems eventually issues a stable nucleation." "Why," I ask, "may one condense on a nucleus from which the soul has fled, and still be permitted to call it an ion? Why, indeed, does the nucleus persist after the ionization has vanished; why does one not get back to dust-free air?" I conclude that "electrification, if present simultaneously with nucleation, is an incidental accompaniment with no immediate bearing on the condensation produced, and for this reason I have endeavored to account for the nucleus at the outset, chemically." It is therefore merely necessary to summarize the point of view in the following statement. Whenever ionization and nucleation are associated in the outcome of any process, physical or chemical, the former is generated proportionally to the latter, in such a way that each is produced at its own rate, depending on incidental conditions. The subsequent life histories of the nucleation and the ionization are distinct, nuclei being often surprisingly persistent, ions by contrast characteristically fleeting. Hence it seems to me best in keeping with all the data in hand, to regard the nucleation as the product which owes its growth or origin to the expulsion (possibly also to the absorption) of the corpuscles representing the concomitant ionization. Moreover ionization should be present only during the period in which the nucleation varies, and a high order of nucleation may be associated with a very low or even vanishing order of ionization. Many phenomena met with in the case of dust-free air seem to be favorable to this view. Ignition and high potential nuclei, X-ray and radiation nuclei in general, phosphorus and water nuclei, produced throughout in dust-free air, all admit of this account of their occurrence and properties; and there is no observable case of a process producing ionization free from nucleation, although there are many cases of nucleation free from ionization.

What becomes of the ionization is a pertinent question: the ions probably vanish by recombination, as they possess strong affinities for each other. Ejected not by atomic but by molecular disintegration, we can scarcely attribute to them phenomenal velocity. They may under favorable circumstances produce fresh nuclei by absorption, by collision, but experiment does not show any appreciable increase of nucleation during the period in which the ionization vanishes. If, however, the velocity of the ion is incremented by the presence of an electric field, the production of fresh nuclei by collision may become perceptible, and the result would then appear as if the nuclei themselves moved in the electric field, whereas they are actually the inert residues left in the wake of a fleeting electron.

Finally, it should be noticed that to produce condensation on X-ray nuclei after long exposure, less than a double supersaturation is needed, whereas in Wilson and Thomson's case of condensation on ions, the supersaturation required is three- to four-fold. Thus the two views of condensation on nuclei and condensation on ions would not in any case be mutually exclusive. Furthermore, if initially (*i. e.*, for short exposures, and nuclei in the extreme state of fineness antedating growth) the nucleation is supposed to have ejected but one electron per nucleus (an assumption which in one form or another must be made in any other explanation), the present view is in no way incompatible with J. J. Thomson's method of measuring the charge of one electron.

If a nucleus like that of phosphorus, for instance, shows a continued tendency to grow, until it finally appears as part of a visible smoke, there may be continuous ejection of electrons within certain limits, as the growth matures. In such a case, electric conduction through a gas freighted with these nuclei would obey Ohm's law, as is actually the case for phosphorus.[1]

To return from this digression to the present volume: the contents of the first two chapters bear on my "Experiments with ionized air." The second chapter originally carried the working hypothesis into further development, but as I have not been able to supply the requisite numerical detail, I have retained the experimental parts only. These chapters, like the earlier work, show, I think, that whereas ionization vanishes with characteristic rapidity, the nucleation has a long lease of life by contrast. At the same time the ionization and nucleation produced in any given process are proportional quantities. The

[1] In the time elapsed since these experiments were made, I have carried them much further than stated in the text (cf. *Science*, XXI., 1905, pp. 275 and 563; *American Journ. of Sci.* (4), 1905, XIX, pp. 175 and 349; *Physical Review*, July, 1905), showing among other things that persistent X-ray nuclei pass into fleeting nuclei on removal of the X-ray tube to greater distances from the outside of the fog chamber or on loss of intensity. Such fleeting nuclei become persistent water nuclei on solution. For the case of radium in a sealed aluminum tube surrounded by a wall of lead 1 cm. in thickness, the nucleation is reduced by but 30 % of the value obtained when the lead envelope is absent. Hence the gamma rays which produce but a few per cent. of the ionization are accountable for the greater part of the nucleation.

corresponding cases for nuclei produced by the X-rays are given in the earlier volume and elsewhere.

The following chapters, III, IV, V, VI, have been written to draw a variety of conclusions from the data in my work on the Structure of the Nucleus, which escaped me in the earlier volume, as well as to correct certain errors relating to the quantity of water precipitated under given conditions, and to the diffusion of nuclei, to which I have already called attention elsewhere. Chapter VI, relating to periodic distribution in the colors of successive coronas, shows under what conditions the angular diameter of a ring of a given color may be used for the estimation of the number of particles producing the observed diffraction pattern. In Chapter VIII a definite practical application is made, for use in the last chapter of the book.

Chapter VII shows a method by which fog particles, even of minutest size, may be measured under the microscope, or microscopically photographed. The peculiar difficulties encountered in the interpretation of these results, in spite of the fact that fog particles are obtained in definite sizes and numbers, are considered critically.

The chief results of the book, however, are given in the last chapter, which is a record of over two years of observation of the number of nuclei present per cubic centimeter of the atmosphere of the city of Providence. The nuclei are abundantly represented, particularly in the winter months. Curiously enough, the maxima and minima appear at about the time of the winter and summer solstices respectively. The reason for this cannot be sought in the astronomical circumstances involved, but must be atmospheric in character. I have supposed that in addition to rain, light pressure, which must be more effective as the days are longer, may have something to do with this. Under any circumstances a highly nucleated medium is an interesting medium. Since much of the nucleation must be of local origin and referable to combustion, the question arises, what has become of the ionization which was simultaneously generated? It has probably vanished as does the ionization in the experimental condensation chamber in the laboratory.

To reply to these questions systematically, observations have now for nearly a year been taken at Providence and at Block Island simultaneously. The latter station has many of the meteorological elements of Providence, but Block Island lies sufficiently in the sea, and is in winter at least sufficiently free from human habitation to present entirely different conditions as to nucleation. I have also in progress a continuous series of observations on the changes in the lapse of time of the nucleation of dust-free (filtered) air, *i. e.*, of air free from foreign nuclear ingredients. The results will be reported in due course elsewhere.

CARL BARUS.

BROWN UNIVERSITY, January 9, 1905.

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A CONTINUOUS RECORD OF ATMOSPHERIC NUCLEATION.

By Carl Barus,

HAZARD PROFESSOR OF PHYSICS AT BROWN UNIVERSITY.

CHAPTER I.

THE RELATION OF IONIZATION TO NUCLEATION IN AIR AFTER CONTACT WITH PHOSPHORUS.

1. *Introductory.*—The opinion was expressed in my earlier papers, that wherever there is sufficiently intense ionization, there one may also expect to find active nucleation; for it is hardly probable that a group of dissociated molecules, neutral as a whole, can ultimately escape combination with each other and the medium in which they are suspended. If these combinations occur in the presence of water vapor, and particularly in a saturated atmosphere, the nuclei due to solution may result. When the nuclei are produced from dilute solutions by shaking, evaporation of the fog particle to the nuclear diameter might be inferred; similarly, when the solute is produced by any kind of radiation or emanation, each trace of solute may grow in bulk by absorbing water to the nuclear stage. In case of an intense emanation like that from phosphorus, this process may actually continue until a visible cloud is produced and the nuclei attain the size of fog particles. But it is to be borne in mind that the nucleus, dissolved or not, is present initially, and is in case of phosphorus producible in dry air; whereas, in case of water nuclei produced by shaking or by jets, there is no evidence of evaporation from the comminuted water particles, nor is it certain that the nuclei here are mere water dust. One must keep in mind that a nucleus may be the residue after the corpuscles representing the ionization have been expelled.

2. *Method proposed.*—If the original emanation, highly ionized though neutral as a whole, is put through the process of condensation, then, if the negative ions are more efficient as condensation nuclei than the positive ions, the nuclei after condensation, or even after remaining in a saturated atmosphere,

should become continually more positive,—assuming that a greater number of negative ions are removed by condensation.

The investigation would therefore consist in testing the ionization immediately coming from phosphorus as to its power in dissipating positive and negative charges, and in comparing these results with the degree of ionization after the emanation has produced condensation. In other words, it is to be ascertained whether the nuclei after a succession of condensations become continually more positive.

The results to be discussed in the following paragraphs have made this apparently straightforward investigation of little avail: for after the emanation has reached the nuclear stage, scarcely 3 per cent. of the original ionization is left. The residue is then so small that a decision of a possible excess of positive or negative ionization is difficult, because the whole is now of the same order as the normal leakage of the electrometer.

In fact, the decision as to whether the positive or negative ionization is in excess is now of very secondary interest, for the nuclei introduced into the condensation chamber have already lost all but a trifle of their original charges. The successive and even the initial condensations thus virtually proceed without electrification.

The initial intense ionization nearly vanishes even in a moderately dry atmosphere. Indeed, it is hard to understand how a neutral, intensely ionized emanation can be produced from a body like phosphorus. It appears to me that the emanation is a molecular body which is stable in the presence of an excess of phosphorus, *i. e.*, at the surface, but which becomes unstable and breaks to pieces in presence of an excess of air, on leaving the phosphorus. The observed ionization is the accompaniment of this dissociation, and occurs on the passage from the first environment to the second. If the ions were produced by phosphorus directly, one would expect them to be either positive or negative, but not neutral.

3. *Water nuclei.*—After finishing the work with phosphorus, correlative experiments with water nuclei were undertaken. It was found necessary, however, to produce them in greater number than is possible by mere shaking, to obtain marked effects. Hence jets were resorted to and studied in some detail, as will be shown in succeeding chapters. The results obtained, though closely resembling the phosphorus data in the main, differed from them inasmuch as the currents above a certain potential difference were constant, and independent of the electromotive force of the condenser, while the ionization or charge is not neutral as a whole. Nucleation again remained equally effective after the ionization had all but vanished in the speedy way observed for phosphorus. Here, too, however, it may be plausibly argued that the nucleus is the stable product after the corpuscles representing the ionization have been extruded.

4. *Comparison of the steam jet and the condensation chamber.*—A digression may here be made relative to the indications of the colors of the steam jet and

of the coronal phenomena, in relation to the number of nuclei concerned. The usual and strong response of the steam jet is for axial blues and greens as far as the purples of the second order. These are already too weak to be of effective service for measurement. But at this stage of smallness of fog particle, the coronal display has but begun. The strong blues of the axial colors correspond to the diffuse gray fogs of the condensation chamber out of which the coronas are gradually evoked when the number of particles [1] has sufficiently diminished. The two instruments are thus in a measure supplementary; the condensation chamber gives intense evidence of the presence of nuclei long after the steam jet would imply their absence. It is for this reason that ordinary smokes like sal ammoniac do not affect the steam jet [2] where a number of nuclei exceeding a certain lower limit is necessary. The latter again is particularly active for those intense and fresh nucleations which produce the browns and yellows of the first order, implying conditions which it is impossible to produce in the condensation chamber at all, until the lower limit of spontaneous condensation of dust-free moist air has been exceeded.

5. *Decay and absorption.*—To account for the rapid diminution of the number of nuclei in the phosphorus emanation in the lapse of time, two hypotheses are prominent. With finely divided and in so far highly potentialized matter (possibly ionized positively and negatively), combinations of nuclei may occur to the detriment of the number of independent nuclei. Such a decrease would take place as the square of the number. On the other hand, it is equally probable that the initial and very small nuclei are in rapid motion much like molecules, and that the loss takes place by absorption or arrest at the walls of the vessel. In my memoir on the subject, I included both hypotheses in the computation; but finding that the phenomena could be adequately explained by the latter, I ignored all spontaneous decay. Though this policy would not be generally admissible, it is unlikely that nuclei can vanish initially at the same rapid rate as the ionization. Indeed, evidence will show that it does not. In case of water nuclei, which are much the more sparsely distributed, the original number of nuclei can be proved by coronas to have varied but little in the short time in which the ionization falls off to a few per cent. Hence the nuclei must be regarded as parting with their charges more rapidly than they are themselves absorbed in the lapse of time, and one will have to distinguish between the velocity of the uncharged and of the charged nucleus in the electric field, the latter being incremented by the electric forces. The cases will be worked out in the chapters below.

6. *Apparatus.*—The apparatus used in the present experiments was capable of a great number of variations. The essential purpose is to enable the observer either to introduce phosphorus emanation at once into the electrical condenser or else to introduce it after it has been saturated with water, suddenly

[1] *Phil. Mag.* (6), iv, p. 24, 1902; cf. *Structure of the Nucleus*, Chapter III.

[2] Thus smoke due to sal ammoniac if introduced into the steam tube will actually clear the blue field produced by phosphorus nuclei, *i. e.*, will wipe out the condensation.

cooled, or otherwise treated. The following diagram, figure 1, will make the adjustments clear.

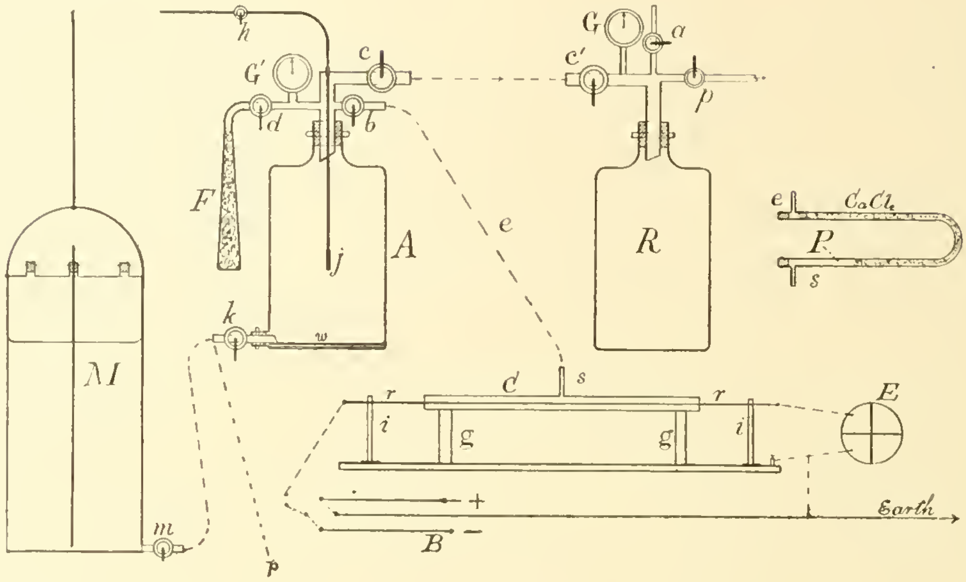


FIGURE 1.—APPARATUS FOR COMPARING NUCLEATION AND IONIZATION. *A*, CORONAL CHAMBER; *R*, EXHAUSTION RESERVOIR; *M*, MARIOTTE FLASK; *C*, TUBULAR CONDENSER; *P* (TO BE INSERTED IN THE CONVEYANCE TUBE, *e*), PHOSPHORUS IONIZER; *G* AND *G′*, VACUUM GAUGES; *F*, COTTON FILTER; *B*, STORAGE BATTERY TERMINALS. TUBE *p* TO SUCTION PUMP, *a* TO ATMOSPHERE, *c* AND *c′* FOR EXHAUSTION, *e* FOR CONVEYING NUCLEI INTO CONDENSER, *d* FOR FILTRATION, *h* FROM THE HYDRANT. SUPPORTS *g*, *g*, ARE METALLIC, *i*, *i*, INSULATING.

The parts of the train of apparatus are the large copper Mariotte flask *M*, with a supply of water sufficient for aspiration, the condensation chamber *A*, used both for producing coronas and for the aspiration and storage of air laden with phosphorus nuclei, the exhaustion chamber, *R*, the phosphorus ionizer, *P*, the tubular electrical condenser, *C*, and the electrometer, *E*. An accessory desiccator, *D*, of the tower form may be inserted on the way, when dry air is needed, as shown in figure 2.

R is connected through a stopcock with the suction pump at *p*, with the atmosphere at *a*, and by wide tubing with the condensation chamber, *A*. It carries a vacuum gauge, *G*.

A is connected with a stopcock with the cotton filter, *F*, with the ionizer by *b* (where the tall desiccator may be inserted), with *R* by *c*, and also carries a vacuum gauge, *G′*. *A* is further joined by stopcocks with the Mariotte flask, *M*, for aspiration, and is graduated in liters on its side. It holds about 10 liters.

The ionizer, *P*, is a large *U* tube containing calcic chloride for desiccation, kept in place by loose cotton plugs. One shank is nearly empty, and at *g* carries thin pellets of phosphorus between strips of wire gauze.

The condenser is tubular, 2.10 and .64 cm. in diameter and 50 cm. long, with the outer mantel permanently put to earth. The core is a brass rod, supported on hard rubber insulators, i, i, about 15 cm. long, and at a distance of 10 cm. from the end of the tube. This rod is highly charged from the storage battery, B, and the leakage found from the electrometer, E, one pair of quadrants of which are in connection with r, r, and the other pair put to earth. A commutator enables the observer to use either the positive or the negative pole of the storage battery for charging the system.

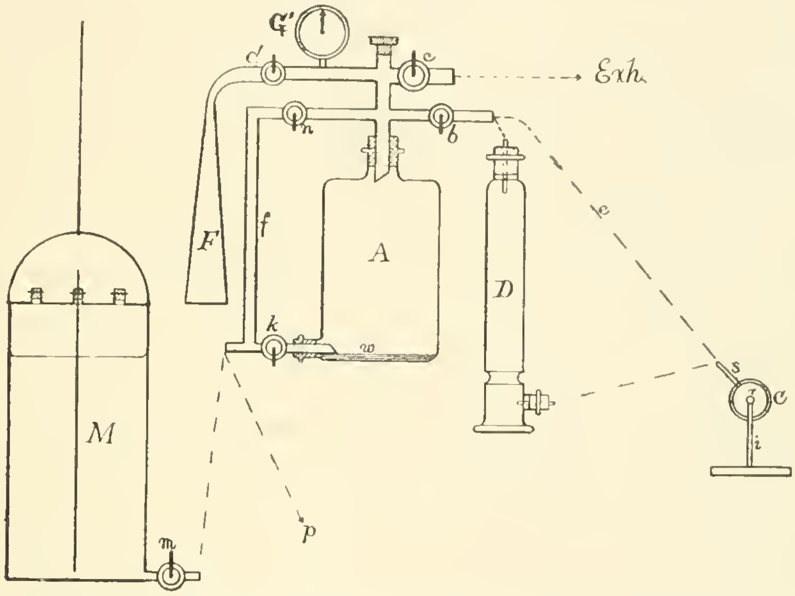


FIGURE 2.—MODIFICATION OF PRECEDING APPARATUS WITH SIDE INFLUX TUBE, k, f, n, FOR MAINTAINING CONSTANT PRESSURE IN A, AND REMOVABLE DESICCATOR, D.

The electrometer was specially built for the present purposes, and the needle was kept charged by a water battery of 48 volts, one pole of which was earthed. The suspension is a silk bifilar moistened by a dilute solution of any hygroscopic salt, and the battery charge is conveyed through the fibers. The quadrants are supported on hard rubber insulators 10 cm. long. Difficulties were encountered in using this apparatus as will appear below. In figure 2 a side tube, f, between stopcocks k and n has been added, with the object of securing greater constancy of pressure in A, the flow of water from M being via m f n.

7. *Manipulations.*—On raising the Mariotte flask, M, and opening appropriate stopcocks, the emanation passes directly from the ionizer into the condenser, and its ionization may be measured. A tower desiccator is here to be inserted before P, to dry the air.

On lowering M, removing D, and reversing P, the emanation passes into A. Here its nucleation may be tested by condensation, and it may thereafter be introduced into C at once or after a number of condensations. The nucleation may also be stored in a dry vessel between D and P reversed, and subsequently transferred from the dry vessel into the condenser.

Finally, the phosphorus ionizer P and D may be quite removed and replaced with a pipe connection, while the tube n f is adjusted for spraying. The hydrant water passing h under high pressure reaches the jet j, placed suitably within A. The water nuclei thus producible may be tested either by coronas or electrically by passing them into the condenser, C. Compare Chapter II.

IONIZATION OF PHOSPHORUS NUCLEI COLLECTED OVER WATER.

8. *Data.* The current through the condenser follows a law similar to Ohm's. The constant appropriate for the comparison of the data may therefore be computed logarithmically. If C is the capacity of the apparatus in parallel, E the potential of the condenser, i the radial electric current through it, R its ohmic resistance for the given medium, s the deflection at the electrometer,

$$(dE/dt)/E=(ds/dt)/s=1/CR, \text{ or } d(\log s)/dt=.434/CR=a$$

where common logarithms are used and a is the constant sought. Thus a varies directly with the conduction of the ionized medium traversing the condenser.

TABLE 1.—IONIZATION OF PHOSPHORUS NUCLEI.

dV/dt (IN LITERS PER MIN.) VARIABLE. NEGATIVE CHARGE.

Time.		Deflection.	a	Remarks.
t	m	s cm.		
I.	10	13.5	.0073	Insulation (morning).
	5	12.5		
	10	11.5		
	15	40.5		
II.	0	9.3	.0097	Insulation (afternoon).
	3	8.8		
	7	7.8		
III.[1]	0	9.3	.013	Slow current of P nuclei (1 L/min.) from aspirator (over water).
	1	8.9		
	2	8.7		
	3	8.5		
IV.	0	8.4	.009	Faster current (same nuclei).
	1	8.3		
	2	8.1		
	3	7.9		
V.	0	9.3	.0078	Do. (same nuclei).
	4	8.5		
	8	7.9		
	12	7.5		
VI.[2]	0	9.5	.014	Very fast current of wet P nuclei. 10 L/min.
	1	9.2		
VII.	0	9.7	.008	P nuclei enter by diffusion through middle tube of condenser.
	1	9.5		
	2	9.3		
	3	9.2		
VIII.	0	9.0	.007	P nuclei blown in with moist air very slowly.
	1	8.7		
	2	8.6		
	3	8.5		

[1] Nuclei put into receiver (A) by preliminary exhaustion.
[2] In this and the other cases fresh nuclei were aspirated into A by passing room air over phosphorus.

TABLE 1.—*Continued.*

Time.		Deflection.	a	Remarks.
t	m	s cm.		
IX.	0	12.8	.321	P nuclei enter directly into condenser. Tubular ionizer.
	1	5.7		
	2	2.6		
	3	1.5		
X.	0	9.8	.014	Current stopped; observation within 5 m.
	1	9.4		
	2	9.1		
	3	8.9		
XI.	0	7.0	.203	Tubular ionizer. Very slow current (L/min.) into condenser directly.
	1	4.1		
	2	2.6		
	3	1.7		
XII.[1]	0	11.10	.016	Nuclei from receiver. Very fast current.
	1	10.70		
XIII.	0	7.4	.320	Slow air current through tubular ionizer into condenser.
	.5	3.7		
	1	1.6		
	1.5	.9		
	sec.			
XIV.	0	4.3	.054	Insulation immediately after air current stops.
	10	4.0		
	20	3.9		
	30	3.7		
	40	3.7		
	50	3.7		
	60	3.6		
	70	3.6		
XV.	0	9.7	.0085	Insulation.
	16m	7.1		

[1] In this and the other cases fresh nuclei were aspirated into A by passing room air over phosphorus.

TABLE 2.—SUMMARY OF THE PRECEDING. NUCLEI INTRODUCED INTO RECEIVER BY ASPIRATING ROOM AIR OVER PHOSPHORUS.

	Remarks.	$a \times 10^3$
I.	Insulation (morning)	7
II.	" (afternoon)	10
V.	Slow current of phosphorus nuclei (liters per min.) in saturated moist air	8
VI.	Do., but fast current (10 liters per min.)	14 to 16
VII.	Phosphorus nuclei enter condenser by diffusion	8
VIII.	Blown in with moist air (slowly)	7
IX.	Phosphorus nuclei enter *directly* from tubular ionizer. Fast current of moist air	320
X.	Air current stopped; observation within 5^m	14
XI.	Slower moist air current through tubular ionizer directly into condenser	200
XIII.	Do. Slow moist air current, but fresher phosphorus	320
XIV.	Ionized air current stopped: immediately after	54
XV.	Insulation	8

Cases V, VI, tested for coronas, gave the usual intense and full series, beginning with diffuse dense fogs.

Table 1 contains the direct observations, time in minutes, and deflections, s, of the electrometer in centimeters. dV/dt, denoting the volume of nucleated air put into the condenser per minute, is here estimated. The charge of the core is negative.

Table 2 gives a summary of these results, among which may be mentioned the following: The insulation is not above $a = .01$ and usually lower. It is not exceeded when phosphorus nuclei have access merely by diffusion (VII), nor on being blown in from a wide vessel (VIII), the charge vanishing on the way. The leakage is not exceeded when a slow current of highly nucleated air stored over water is passed through the condenser (V), and but slightly for the case of a fast current of such nucleated air (VI) taken out of the receiver A in the figure.

By contrast, the excessive ionization ($a = .2 - .3$), if the nucleation is at once introduced into the condenser, is striking enough. Hence scarcely 3 per cent. of the original ionization has survived after short storage in the receiver in spite of the extreme density of nucleation which the coronas would cotemporaneously show. In fact, the ionization dies out almost at once in the condenser (X–XIV), even in the absence of water vapor.

9. *Further data.*—The experiments were now repeated as in table 3, with the résumé of results shown in table 4. These are substantially like the above. With fresh phosphorus the residual ionization of the nuclei-bearing air after short storage over water is but a few per cent. of the original ionization. It was supposed that on drying the nucleated air over phosphorus pentoxide, before passing it into the condenser, the original ionization might be in part regained, but the table shows not a trace of this.

TABLE 3.—IONIZATION OF PHOSPHORUS NUCLEI. dV/dt = ABOUT 2 LIT./MIN. NEGATIVE CHARGE.

Time.	Potential.	a	Remarks.
t m.	s		
0	15.8	.009	Room air (insulation).
2	15.2		
4	14.6		
6	13.9		
0	20.5	.024	Slow current of P nuclei in damp air.
1	19.4		
2	18.5		
3	17.6		
0	18.9	.011	Filtered moist air.
1	18.4		
2	17.9		
3	17.5		
0	21.1	.010	Room air.
1	20.7		
2	20.2		
3	19.7		

TABLE 3.—*Continued.*

Time.	Potential.	a	Remarks.
t m	s		
0	19.6	.021	Current of P nuclei in damp air passes over P_2O_5.
1	18.6		
2	17.7		
3	17.0		
0	10.8	.017	P nuclei in damp air without P_2O_5 (small deflection).
1	10.4		
2	10.0		
3	9.6		
0	23.1	.008	Room air.
1	22.6		
2	22.2		
3	21.9		
0	20.9	.018	P nuclei in damp air (large deflection).
1	20.2		
2	19.4		
3	18.4		
0	24.7	.264	P nuclei directly from ionizer.
1	13.4		
2	7.1		
3	4.1		
0	26.0	.286	Do. Aspirator more constant.
1	14.4		
2	6.9		
3	3.9		

TABLE 4.—RÉSUMÉ.

	$a \times 10^3$	$a \times 10^3$ corrected.
Insulation (room air)	8–10	0
Filtered damp air	11	0
[1] Nucleated damp air (1) (fresh P)	24	14
[1] Nucleated damp air partially dried	21	11
[1] (2)	17	7
[1] (3)	18	8
[2] Phosphorus nuclei direct (1)	260	250
[2] (2)	290	280

[1] From condensation chamber.
[2] From ionizer.

The charge in the condenser is negative as before. It should be more rapidly dissipated if negative ions are precipitated more rapidly in the receiver, than a positive charge. To obtain dense nucleation, room air was again aspirated over phosphorus into the receiver, from which it was then discharged as expeditiously as possible, the time taken being from 5–10 minutes.

10. *Effect of different charges in the condenser.*—In the next experiments the sign of the charge was varied. To find comparable results it was thus necessary to maintain a definite current through the condenser, and about 2.5 liters per minute was adopted compatibly with the dimensions of the apparatus.

Nuclei were again aspirated into the receiver over phosphorus. The leakage was apparently different for charges of opposed sign; but this was due to the insulation of the condenser, which is greater for negative than for positive charges. Deducting this, the values of the ionization, a, differ by quantities which lie within the errors of observation.

As the receiver in the course of the efflux of nucleated air shows fogs of continually increasing density, the spontaneous precipitation must have been equally effective for positive and for negative nuclei.

TABLE 5.—IONIZATION OF PHOSPHORUS NUCLEI. CHARGE IN CONDENSER AT 10 VOLTS. $dV/dt = 2.5$ LITERS/MIN.

Charge.	Time.	Potential.	a	Remarks.
	m			
—	0	15.8	.025	Nucleated damp air.
	1	14.9		
	2	14.0		
	3	13.3		
+	0	16.0	.016	Insulation (air ionized?).
	1	15.3		
	2	14.8		
	3	14.3		
+	0	15.5	.022	Nucleated damp air.
	1	14.5		
	2	13.8		
	3	13.3		
+	0	15.3	.022	Nucleated damp air.
	1	14.4		
	2	13.8		
	3	13.0		
—		17.9	.011	Insulation.
		17.3		
		16.9		
		16.6		

TABLE 6.—RESULTS.

	$a \times 10^3$	$a \times 10^3$ (corrected)	Insulation $a \times 10^3 = 10-16$.
—	25	-9	
+	22	$+6$	
+	22	$+6$	
—	18	-8	
+	24	$+8$	
—	17	-7	

In tables 7, 8, similar results are given, but with the insulation tested after each passage of nucleated air through the condenser. The results taken consecutively are shown in table 8.

TABLE 7.—IONIZATION OF PHOSPHORUS NUCLEI. $dV/dt = 2.5$ LITERS/MIN. CHARGE AT 20 VOLTS, 19.6 cm. DEFLECTION.

Charge.	Time.	Potential.	a and a corrected.	a Insulation.	Remarks.
	scale pts.	scale pts.			
+	0	18.4	.018	.009	
	1	17.6	.009		
	2	16.9			
	3	16.3			
—	0	19.0	.014	.002	
	1	18.2	.012		
	2	17.7			
	3	17.2			
+	0	17.3	.018	.009	
	1	16.7	.009		
	2	15.9			
	3	15.4			
—	0	20.9	.010	.001	
	1	20.2	.009		
	2	19.8			
	3	19.4			
+	0	17.7	.023	.012	
	1	16.5	.011		
	2	15.7			
	3	15.0			
—	0	16.2	.018	——	Nucleated damp air.
	1	15.4	——		
	2	14.7			
	3	14.4			
+	0	15.4	.024	——	Do.
	1	14.6	——		
	2	13.8			
	3	13.1			
—	0	16.9	.017	——	Do.
	1	16.2	——		
	2	15.5			
	3	15.1			
—	0	18.8	.010	——	Insulation.
	1	18.6	——		
	2	18.1			
	3	17.7			

TABLE 8.—RÉSUMÉ.

$$\left.\begin{array}{lr} \text{Charge} + & a = .009 \\ - & 12 \\ + & 09 \\ - & 09 \\ + & 11 \end{array}\right\} \text{Mean } .010 = a.$$

There is slight excess of leakage for negative charges; but as the insulation was $10^3 \times a = 9$–12 for positive, and 1–2 for negative charges, these differences are within the uncertainties of observation. One may again note that if the dense spontaneous fogs in the receiver were associated with selective condensation, then negative charges should be more rapidly dispelled.

11. *Dried emanation.*—In the following experiments (table 9) the phosphorus was previously dried over calcic chloride, and then introduced into the receiver from the desiccator and the shortest possible connecting tube. Dry ions thus suddenly came in contact with water vapor, and it was supposed that an unequal reduction of positive and negative ionization might ensue. The ions were stored less than 5 minutes in the receiver, the shortest time practicable. Insulation of the electrometer and parts was determined before and after each measurement with nucleated air.

TABLE 9.—IONIZATION OF PHOSPHORUS NUCLEI.* $dV/dt = 2.5$ LIT./MIN. TESTED AFTER 4-5 MIN.

Charge.	Time.	Deflection.	a	Insulation a.		a Corrected.
	t	s		Before	After	
+	0	14.4	.0152	.0137	.0120	.0023
	1	13.8				
	2	13.4				
	3	12.9				
−	0	15.3	.0070	.0070	.0046	.0022
	1	15.0				
	2	14.8				
	3	14.6				
+	0	14.7	0.0135	.0096	.0092	.0041
	1	14.3				
	2	13.8				
	3	13.4				

* Phosphorus nuclei dried over calcic chloride and conveyed by a dry current of air, before storing over water

The residual ionization so obtained, $a = .002 - .004$ for positive and .002 for negative charges, is smaller than heretofore, but again practically neutral. Thus very dry phosphorus nuclei seem to lose their ionization quicker than if placed in ordinary air; but changes of the activity of the ionizer may account for the difference.

12. *Wet emanation.*—For contrast, the nuclei were conveyed into the receiver (table 10) in a wet current of air passing over phosphorus. A U-tube was used, one leg of which contained wet sponges and the other the phosphorus grid, the damp air from the former sweeping over the latter into the receiver. The ionization found is distinctly greater[1] than the dry air data of the last table, though it does not exceed the usual values for room air. The difficulty of keeping the ionizing activity constant is again involved. According to the table, positive charges are more rapidly discharged than negative charges, which would indicate an excess of negative ions comparable to the case of water nuclei in the next chapter.

[1] *American Journal of Science* (4), XII, p. 327, 1901.

TABLE 10.—IONIZATION OF PHOSPHORUS NUCLEI.[1] $dV/dt=2.5$ LIT./MIN. TESTED AFTER 5–10 MIN.

Charge.	Time.	Deflection.	a	Insulation a.		a Corrected.
	t	s		Before	After	
+	0	8.9	.0207	.0098	.0098	.0109
(10 cells)	1	8.4				
	2	8.0				
	3	7.7				
—	0	10.4	.0117	.0054	.0089	.0046
(10 cells)	1	10.2				
	2	9.9				
	3	9.6				

[1] Phosphorus nuclei conveyed in a damp current of air. Tested for coronas, the nucleated air of the receiver shows the usual strength.

13. *Residual ionization after one hour.*—The storage of phosphorus nuclei over water in the above experiments did not exceed 10–15 minutes. It was thought that by giving the fog particles more time to subside, the sign of the residual ionization might become apparent, supposing that more negative nuclei are precipitated. The results in table 11 are peculiar: whereas the positive charges in the presence of the nucleation vanish more slowly than for room air, the negative charge vanishes much faster. This would make an

TABLE 11.—RESIDUAL IONIZATION OF PHOSPHORUS NUCLEI AFTER ONE HOUR. $dV/dt=2.5$ LIT./MIN. CHARGE AT ABOUT 20 VOLTS, OR LESS.

Charge.	Time.	Deflection.	a	a Corrected.	Remarks.
	t	s			
+	0	23.9	.0121	.0121	Room air.
(10 cells)	1	23.3			
	2	22.7			
	3	22.0			
	4	21.4			
	5	20.9			
+	0	20.6	.0107	.0014	Damp nucleated air.
	1	20.0			
	2	19.5			
	3	19.0			
	4	18.6			
	5	18.2			
—	0	24.7	.0068	.0068	Damp nucleated air.
(7 cells)	1	24.4			
	2	24.1			
	3	23.6			
	4	23.2			
—	0	23.0	.0036	+.0032	Room air.
	1	22.7			
	2	22.5			
	3	22.4			
	4	22.2			
	5	22.0			

excess of $a = .005$ of residual positive nucleation over the negative nucleation, and it would follow that the negative nuclei are precipitated faster. But with a leakage in the electrometer of .011 and .004 respectively, without any ionized medium, the result is not guaranteed, particularly as the positive leakage is large.

14. *Nucleation partially precipitated.*—The nucleated air stored over water in the receiver, *A*, was suddenly cooled and allowed to subside 5–10 minutes. In this way greater chance was given for the differentiation of positive and negative nuclei. The corrected values of *a* show that positive charge is removed faster than negative charge, by $a. = .0010$ and .004 respectively, implying excess of negative nuclei. With the insulation varying from .003–.010 and .003–.013, before and after some of the measurements, this result is again doubtful. It should be noticed that it is the reverse of the preceding.

TABLE 12.—RESIDUAL IONIZATION AFTER PARTIAL PRECIPITATION. $dV/dt = 2.5$ LIT./MIN. CHARGE AT 10 VOLTS.

Charge.	Time.	Deflection.	*a*	*a* Corrected.	Remarks.
	t	*s*			
—	0	13.0	.013	.004	Nucleated air. Subsiding 4^m without exhaustion and 6^m with exhaustion. Insulation before $.003 = a$.
(5 cells)	1	12.9			
	2	12.4			
	3	12.0			
—	1	11.0	.015	0	Room air.
	2	10.6			
	3	10.3			
	4	9.9			
+	1	17.4	.022	.014	Nucleated air. Subsiding 4^m without exhaustion and 8^m with exhaustion. Insulation before $.002 = a$.
	2	16.6			
	3	15.6			
	4	15.0			
	5	14.1			
+	1	13.8	.013		Room air.
	2	13.7			
	3	13.4			
	4	13.0			
	5	12.4			
	6	12.1			
—	1	11.8	.019	.010	Nucleated air. Subsiding 4^m without exhaustion and 12^m with exhaustion. Insulation before $.0079 = a$.
	2	11.5			
	3	11.0			
	4	10.5			
	5	9.9			
—	1	9.6	.009		Room air.
	2	9.3			
	3	9.2			
	4	9.0			
	5	8.8			
	6	8.5			

15. *Ionization of dry phosphorus nuclei.*—In the present experiments a dry vessel of 10 liters capacity was introduced between the tower desiccator and the tube, *P*, figures 1 and 2. Phosphorus nuclei were now aspirated into this

vessel. They were discharged after 5 minutes into the condenser after removing the phosphorus tube. Table 13 shows that almost all the ionization is lost by this dry storage as the excess of leakage due to the discharge of the dry air through the condenser is $a=.000$ and .007, respectively. Thus dry air shows no preservative effect.

TABLE 13.—RESIDUAL IONIZATION AFTER DRY STORAGE OF PHOSPHORUS NUCLEI.[1] $dV/dt=2.5$ LIT./MIN. CHARGE AT 10 VOLTS.

Charge.	Time. t	Deflection. s.	a	a Corrected.	Remarks.
−	0	14.4	.006	.000	Phosphorus stored dry 2–5^m
(5 cells)	1	14.1			
	2	13.9			
	3	13.7			
−	0	11.7	.006		Room air.
	1	11.6			
	2	11.4			
	3	11.3			
+	0	13.7	.011	.007	Phosphorus stored dry 2–5^m
	1	13.4			
	2	13.0			
	3	12.6			
+	0	11.7	.004		Room air.
	1	11.6			
	2	11.5			
	3	11.4			

[1] Intense antecoronal fogs obtained in the exhausted receiver, A, due to back motion of the nuclei into the receiver through the aspirators.

In table 14, by a modification of the apparatus, a current of dry air passes from the desiccator over phosphorus, and then into one end of a dry vessel of 10 liters capacity. At the other end of the vessel the air is continually discharged into the condenser. But the usual negative result appears.

TABLE 14.—DRIED PHOSPHORUS IONS PASSED INTO A DRY VESSEL AND THEN CONTINUOUSLY INTO THE CONDENSER. $dV/dt=2.5$ LIT./MIN. CHARGE AT 10 AND 20 VOLTS.

Charge.	a	Remarks.
−	.017	P ions.
(10 cells) −	.000	Room air before and after.
(15 cells) −	.012	P ions.
−	.000	Room air before and after.

16. *Inferences.*—The chief result of the investigation is the enormously rapid reduction of the ionization of the phosphorus emanation in contrast with the persistence of the nucleation. In other words, only a few per cent. of the

original ions are associated with the nuclei by which the dense fogs and coronal sequences are produced, even at the outset. It was with a view to possibly restoring some of this lost ionization that the great variety of experiments detailed in the chapter were undertaken; but not a trace of restoration was observable in any case.

Moreover, the whole of the original ionization vanishes symmetrically, for the nuclei as a whole are neutral throughout. At least with so insignificant a residue of the original ionization, the decision as to whether more positive or more negative ions have vanished is a delicate one and of trifling interest in this connection. For the phenomena are now all of the order of the leakage of the electrometer and appurtenances. If when 100 ionized nuclei of the phosphorus emanation are suddenly introduced into an atmosphere saturated with water vapor, the ionization of 96 has vanished without a record, while the remaining 4 are in equal number positive and negative, it is unlikely that negative ions can have greater affinity for water vapor or be more remarkable in their efficiency as condensation nuclei than positive ions.

Finally, it does not appear that the ionization lost so soon after the removal of the emanation from the phosphorus surface can ever be restored, notwithstanding the fact that in the condensation chamber nuclei may be made to pass from the fog particle to the nuclear stage of size and density an indefinite number of times. Hence it follows that it is the ante-nuclear stage by which the ionization is introduced.

In one respect the experiments with phosphorus are unsatisfactory: it takes some time before the condensation chamber can be adjusted for condensation on the phosphorus nucleus as it is necessary to introduce the nucleation from without. Placed within the chamber over water, phosphorus emits a dense filament of smoke, and is relatively inefficient. With water nuclei there is no such difficulty; for here the nuclei are most efficiently produced in the condensation chamber itself, while the ionization may be studied without loss of time. The results are given in the succeeding chapter.

As a whole, the experiments agree well with the original hypothesis, that nuclei and ions are distinct entities; that the former constitute the residual product left after the corpuscles representing the ionization have been expelled. Radio-activity in case of the relatively gentle breakdown of molecular structure here in question can hardly be anticipated. If a nucleus, like that of phosphorus, for instance, shows a tendency to grow continuously, until it finally appears as part of a visible smoke, there may be continuous ejection of electrons. In such a case electric conduction through the gas freighted with these nuclei would follow Ohm's law, as is actually the case for phosphorus.

CHAPTER II.

RELATION OF THE IONIZATION AND THE NUCLEATION ASSOCIATED WITH WATER NUCLEI, PRODUCED IN AIR.

IONIZATION PRODUCED BY SHAKING SOLUTIONS.

1. *Introduction.*—In the present chapter there will be three subjects for consideration. The endeavor must first be made to detect ionization in water nuclei, produced as in the former memoir,[1] by shaking solutions. As the ionization so recognized proves to be inadequate, the problem next in order will

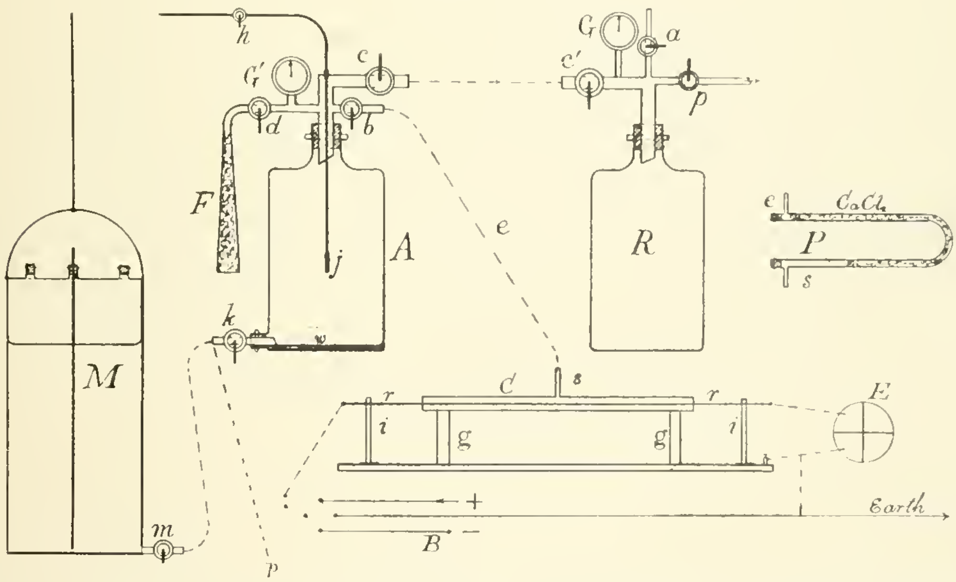


FIGURE 1.—APPARATUS FOR COMPARING NUCLEATION AND IONIZATION. *A*, CORONAL CHAMBER; *R*, EXHAUSTION RESERVOIR; *M*, MARIOTTE FLASK; *C*, TUBULAR CONDENSER; *P*, (TO BE INSERTED IN THE CONVEYANCE TUBE, *e*), PHOSPHORUS IONIZER; *G*, *G*[1], VACUUM GAUGES; *F*, COTTON FILTER; *B*, STORAGE BATTERY TERMINALS. TUBES, *p* TO SUCTION PUMP, *a* TO ATMOSPHERE, *c*, *c*[1], FOR EXHAUSTION, *e* FOR CONVEYING THE NUCLEI INTO THE CONDENSER, *d* FOR FILTRATION, *h* FROM THE HYDRANT. EXTREMELY FINE JETS OF WATER SHOOT OUT FROM THE NEEDLE-PRICKED LEAD PIPE, *j*. SUPPORTS *g*, *g*, ARE METALLIC, *i*, *i*, INSULATING.

be the production of the maximum number of nuclei per cubic centimeter possible, and will be considered in the second section of the chapter. The third will then take up and examine the ionization produced along lines very similar

[1] *Structure of the Nucleus*, Chap. V.

to those of the preceding chapter, and will lead to an examination of the inferences already drawn for phosphorus nuclei.

2. *Apparatus.*—To detect the electrification of nuclei produced by shaking, a 10 per cent. solution of sodic sulphate was employed, as this had been shown to produce the nuclei in largest numbers under otherwise like conditions.[1] The solution was used both to generate the nuclei by vigorously shaking the large aspirator flask, *A*, figure 1, containing a small amount of the solution at the bottom, *w*, as well as to discharge the nuclei into the condenser, *C*, by filling *A* with the liquid coming from the large Mariotte flask, *M*. Raising or lowering the latter enabled the observer either to add liquid to *A*, or to withdraw it. When a constant pressure was needed the device shown in the preceding chapter (figure 2) was used, and the liquid passed along a side tube. The nucleated air is discharged by the pipe, *e s*, into the tubular condenser, *C*, entering at *s*. The core of the condenser is highly charged and connected with one pair of quadrants of the electrometer, *E*, the other pair being earthed and the needle kept charged by a water battery, whose other pole is also earthed. The supports, *i i*, are of hard rubber, those (*g g*) of the outer tube of the condenser are metallic, and together with the base of the apparatus and the pipe, *e s*, are kept at zero potential.

The operations are evident. Having charged the core, the rate of discharge is found when the current of nuclei traverses the condenser, the volume supplied per second being read off on a scale attached to *A*. Results for nucleated air (shaking) are alternated with results for dust-free air obtained by aid of the filter and stopcock at *F*.

3. *Results.*—The results (two independent series) are given in the following tables. The season was damp and unsuitable for electrostatic work, but the

TABLE 1.—ELECTRIC CHARGES OF NUCLEI PRODUCED BY SHAKING A DILUTE SOLUTION OF Na_2SO_4. CHARGE IN CONDENSER, 40 VOLTS. $a=d(\log s)/dt$; dV/dt IN LIT./MIN.

Condenser at	dV/dt	a	Remarks.
+40 volts	1.7	.020	After vigorous shaking.
−40 "	1.7	.022	" " "
+40 "	1.7	.020	Without shaking.
−40 "	1.7	.022	" "

TABLE 2.—Same as preceding.

−40 volts	3.0	.010	Filtered air. Without shaking.
+40 "	3.0	.010	" " " "
+40 "	3.0	.008	After vigorous shaking.
−40 "	3.0	.009	" " "

[1] *Structure of the Nucleus*, p. 121.

data are sufficient to indicate the extreme smallness of the effect to be observed. Ohm's law being assumed as usual, as a rough approximation to the truth, the readings in scale parts, s, are read off, at the successive times, t, of observation. The constant then follows as $a=d(\log s)/dt$ and dV/dt denotes the number of liters of air, nucleated or not as stated, put through the condenser. In table 1 the leakage, a, is larger for negative than for positive charges, but the effect is equally large no matter whether the influx is dust-free and filtered or whether the nuclei produced by shaking traverse the condenser. Shaking is thus without an electrical effect, so far as can here be discerned. What has been observed in both cases is a continuous drift of the needle.

In table 2, for another adjustment, the positive and negative charges leak out equally fast when dust-free air constitutes the medium of the condenser. When shaken nuclei circulate through it, the negative charge leaks out more rapidly than the positive charge, implying positively charged nuclei. But as the result is no larger than for dust-free air, it is again probable that the mere drift of the needle is being observed.

The results from both tables are therefore negative, showing that the excess of leakage for a charge of one sign over that of another must be of the order of .001 when referred to minutes, if the nuclei in question are produced by shaking. This result, however, is not unexpected; for it is not more than about a thousand nuclei that are here available, and with the necessarily small charge residing on each, a detection of the effect will not easily be accomplished in connection with moist air. The following pages, moreover, will show how quickly the charge vanishes, and I am not sure that the experiments were made expeditiously enough. Hence I waived the experiments temporarily, to be resumed with a more efficient method of producing water nuclei and during the dryer atmospheric conditions of winter.

THE EFFICIENCY OF NUCLEI-PRODUCING JETS.

4. *Powerful methods of comminution.*—It appears from the preceding section and elsewhere that the number of nuclei produced by shaking is relatively very small, and the coronas correspondingly simple. To obtain more nuclei a much more violent method of comminution must be resorted to, such as is given if fine jets of water, generated under high pressure, are shattered either against a solid obstacle or against each other. Fortunately, ordinary hydrant water contains enough solute to answer the requirements, and the construction of the jet is thus a straightforward problem. It will be found that for each jet there is a maximum of productivity, and one is thus able to make a series of jets, each corresponding to a definite number of nuclei under like conditions. Each jet has a definite saturation number, and while the maximum saturation producible in this way is naturally far below the efficiency of phosphorus and other chemical ionizers, so far as nuclei are concerned, the aggregate ionization is not very different.

In table 3 the results obtained with jets of a variety of patterns and numbers are given in detail. They were all fed with hydrant water at 60–70 pounds pressure. In these experiments the jet, *j*, replaced the phosphorus, the nuclei being actually produced from the spray in the vessel, *A*, figure 1. Details of a simplified form are given in figure 2, where *j* is the jet to be tested, screwed to a brass pipe, *f*, joined by gas couplings (unions at *U*, etc.) to the pipe *h* from the hydrant. In many of the jets the spray is broken against the sides of the vessel, this being the most efficient mode of comminution. The excess of water is carried off by the cock, *k*, for which there is a side branch, *p*, with a special stopcock. When *k* is closed, the jet may often be used to discharge its own

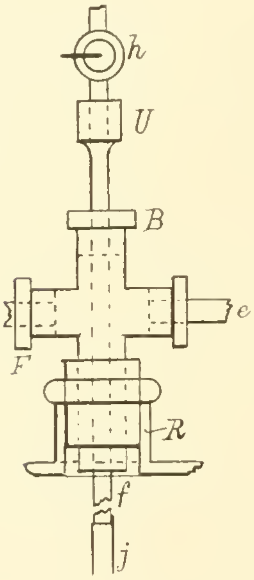


FIGURE 2.—DETAIL (SIMPLIFIED) OF *A*, FIG. 1

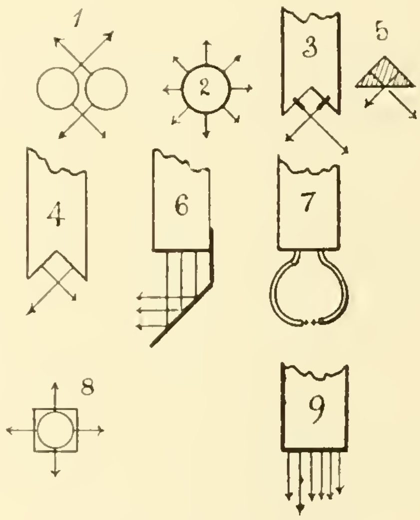


FIGURE 3.—FORMS OF IMPINGING JETS.

nuclei into the condenser without the intervention of the Mariotte flask, *M*, figure 1.

The types of jets used are shown in figure 3 in cross section, and the numbers in the table correspond to those of the figure. In No. 1, two parallel eighth-inch lead pipes emit jets from their sides in such a way as to impinge on each other nearly at right angles. It was not possible to completely or continually shatter both jets mutually in this way. In No. 2, radial jets from a quarter-inch lead pipe impinge on the walls of the receiver; in No. 8 the pipe has been thinned. In No. 3 two capillary adjutages produce jets which impinge on each other, and the same is the case, with evident modifications, in Nos. 4 and 7. In No. 6 an oblique lead buffer has been added, while in No. 9 the jets issue from a finely perforated copper plate, and impinge turbulently on the pool of water below. In addition to these, ordinary lava tips (No. 5) and other steatite jets were used.

The holes were usually pricked with fine cambric needles. Of all the jets, Nos. 2 and 8 were not only the simplest but the most efficient relative to the quantity of water consumed. Adjutages introducing resistances gave inferior results, but are needed for special purposes. To change the efficiency at will, the number of holes may be varied from two to fifty.

5. *Results.*—In table 3 the description of the jet, the corona produced and its serial number, together with the number of nuclei per cubic centimeter corresponding, are given in each case. Certain data of the aperture, *s*, are sometimes added for identification. For convenience in comparisons, a brief table of coronas is subjoined to the next table.

TABLE 3.—NUMBER OF NUCLEI PRODUCED BY DIFFERENT JETS. WATER PRESSURE, 60–70 lbs.

Kind of Jet.	Corona.	s	n	Remarks.
No. 1. One jet.	Simple	2.5	6000	
" 1. Two impinging jets.	"	4.3	30000	
" 1. " " "	"	4.2	29000	After 5^m spraying.
" 1. " " "	"	4.5	40000	" 10^m "
" 1. Twenty " "	g′ b r	6.0	80000	
" 2. Fifty radial jets.	g′ b r		100000	Jets .04 cm. diam.
" 2. 100 " "	g b r		80000	(Lead walls too thick.)
" 3. Short adjutages.	gy o b		80000	Jets .11 cm. diam.
" 3. Do. Mouths flat.	w c g		50000	
" 3. Finer holes.	w r|g	4.2	30000	Jets .05 cm. diam.
" 3. " "	w r|g		30000	" .03 " "
" 4. Six jets.	g′|b|r		40000	Punctured sheet lead.
" 6. Three "	w r|g		30000	
" 7. Two "	w r|g	4.0	25000	Jets .05 cm. diam.
" 8. Thirty "	w p b g r		100000	" .05 " "

It is frequently difficult to place the coronas, and for this reason, several cases, one of which is given in table 4, were investigated by successive exhaustions, as explained in the preceding memoir. The identification of the coronas is then more easily possible, beginning with the green corona. The table also contains direct measurements of the successive apertures, with the number of particles computed therefrom. The results show a peculiar periodic discrepancy, the nature of which will be treated at length elsewhere.[1] For the present, the apertures serve merely for the identification of coronas.

The results obtained for jets will conveniently be discussed in the next section in connection with the electrical data there set forth. Here I need only point out that the maximum nucleation obtainable with jets is obviously dependent on their pressure, number, fineness, etc., and probably on the degree with which the air current simultaneously generated has been removed. The presence of this current eventually sweeps out the nuclei as fast as they are generated, and for this reason it makes no difference whether one begins with

[1] Chapter VI.

filtered or with room air. A jet free from air currents should be most efficient, *cæt. par.* Curiously, the maximum nucleation obtainable with jets lies just

TABLE 4.—EFFECTS OF SUCCESSIVE EXHAUSTION. WATER NUCLEI. ESTIMATED NUCLEATION.

No.	Corona.	s	$n \times 10^{-3}$.
?9	w p b r	—	120
13	w r g	-	75
14	w c|g	—	65
15	w|b|r .	—	45
16	w c|g	3.9	25
17	w|b|r	3.3	12
18	corona	2.8	8
19	"	2.5	6
20	"	2.2	4

Nucleations corresponding to successive coronas:

No. 5	olive	—	No. 13	w, r g	75000
6	w y	200000	14	w c|g	65000
7	w o	180000	15	w p cor	55000
8	w r	160000	16	g′ b p	45000
9	w c	140000	17	w r g	35000
10	w p	120000	18	w c g	25000
11	g b p	100000	19	coronas	20000
12	g′ o	90000			

below the maximum nucleation of atmospheric air as found in the winter observations. Probably this is a mere coincidence.

THE IONIZATION OF WATER NUCLEI.

6. *Introductory.*—In my report to the Smithsonian Institution (August, 1902) and elsewhere,[1] I pointed out the desirability of further investigations on the Lenard [2] effect. While my work in this direction was in progress, a paper due to J. J. Thomson [3] appeared covering similar ground. Nevertheless, I shall venture to publish the following results, since the subject is looked at from a somewhat different point of view, obtained from coronal and other measurements. My chief purpose, however, was to find in what degree the theory given in my experiment with Ionized Air [4] was to be modified to meet the conditions

[1] *Science*, XVI, p. 633, 1902.

[2] Lenard, *Wied. Ann.*, XLVI, p. 584, 1892.

[3] J. J. Thomson, "Experiments with Induced Radioactivity of Air, and on the Electrical Conduction Produced in Gases when they Pass through Water," *Phil. Mag.* (6), IV, p. 352, September, 1902.

[4] *Smithsonian Contributions to Knowledge*, 1309, 1901.

for water nuclei. I have not, however, with the data now in hand been able to complete this to my satisfaction, and have for this reason confined the present chapter to experimental work, to the exclusion of theoretical considerations of the kind given tentatively elsewhere.[1]

7. *Apparatus.* If in the receiver, or condensation chamber, *A*, the metallic pipe, *c*, joining at *b*, leads directly to the tubular condenser, *C* (radii 1.05 and .34 cm., length, 50 cm.), the apparatus, figures 1, 2, takes the form adapted for measuring the initial ionization of the nuclei. If the cocks *k* and *d* (filter) are closed and the fine radial jets are put in action by opening the water faucet *h*, the charged air is gradually expelled through *b* as the water level in *A* rises. When an efficient jet is used the rate is usually about 2 liters/minute. This velocity may be increased or diminished by aid of the flask, *M*, figure 1, attached at *k*.

Since the jets, *j*, impinge on the walls of the vessel, this is kept uniformly moist or better coated with water, and therefore continually put to earth by the hydrant connection. Similarly the pipe, *c*, leading to the outer coating of the condenser is with this continually put to earth. The core of the condenser, insulated by long hard rubber supports, retains charge well even at high potentials, and in spite of the damp gases, because of the remoteness of the supports.

8. *Results. Initial charges.*—The following table gives the data obtained, when the nuclei generated by the spray are *at once* passed into the tubular condenser, whose inner surface is charged as stated, the outer being put to earth.

TABLE 5.—IONIZATION OF WATER NUCLEI. $dV/dt=2$ LIT./MIN. TOTAL CAPACITY OF ELECTROMETER AND CONDENSER, 72 cm.

Condenser charge.	Insulation before.	a	Insulation after.	ds/dt. cm./min.
+20 volts	$a=.013$	.338	$a=.010$	.79
		.490		.71
−20 volts	$a=.020$	.072	$a=.002$	.32
		.091		.38
		.108		.40
		.124		.40
+20 volts	$a=.022$	.223	$a=.015$	.79
		.335		.78
		.498		.71
		.872		

The method consisted in testing the insulation of the condenser, immediately before and after the introduction of water nuclei. The table gives the deflection in centimeters, after intervals of 1 min., $\frac{1}{2}$ min., and 1 min., in each of the cases, respectively. The conduction, $a=\delta(\log s)/\delta t$, is computed by assuming Ohm's law; but in case of the medium of water nuclei, it is seen at once that Ohm's law does not apply, and that the conduction, a, increases enormously as

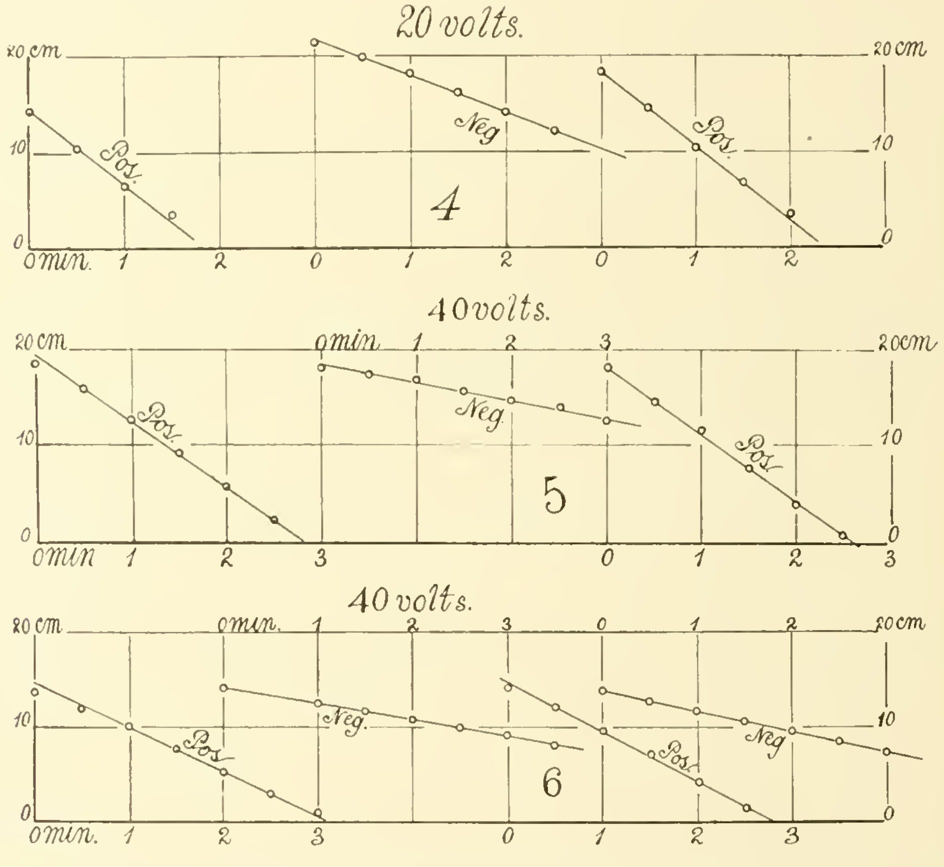
[1] *American Journal of Science* (4), XV, 1903, p. 105; *ibid.*, p. 217.

the charge on the condenser vanishes. The average value of the conduction, moreover, is quite of the order of values found for phosphorus nuclei in the above tables, under similar circumstances. As the data in the table show a for successive minutes, its variation in the last series is from .223 to .872 in 3 minutes.

Since $2.3\, aC = 1/R$, where $C = 8/10^{11}$ farads is the capacity of the condenser and appurtenances, the initial and final resistance would be

$$R = 25 \times 10^9 \text{ and } R = 6 \times 10^9 \text{ ohms.}$$

It follows then that if the equation of the current be taken, or $i \propto n(U+V)e\ (E/l)$ in the usual notation, the number of charged nuclei, n,



FIGURES 4, 5, 6.—CURVES SHOWING ELECTROMETER DEFLECTION (LEAKAGE) AFTER CONSECUTIVE HALF MINUTES, FOR DIFFERENT CHARGES AND POTENTIALS IN THE CONDENSER.

increases as the potential difference, E, diminishes. The same is true for the negative current with a smaller coefficient.

The results for the conduction, a, become more interesting if the electrometer deflections are charted graphically in relation to time as in the annexed figures 4, 5, 6. It is thus seen that the current is surprisingly constant, while the initial potential difference of about 20 volts gradually quite vanishes.

9. *Comparison with coronas.*—The number of ions which may be computed from the given currents is excessive when compared with the number of

nuclei, particularly when considered in parallel with the corresponding case of phosphorus. The contrast would be even more striking if the water nuclei could be tested immediately after production. Several inferences are thus suggested: either the charge of each nucleus is many electrons, or nuclei are lost at the outset at a rapid rate (this is disproved by experiment), or each nucleus emits many electrons.

10. *Evanescence of the charges of water nuclei.*—The same remarkable contrast between the initial charges and the subsequent charges on the nuclei that has been already pointed out for phosphorus will now be observed, if only a little time is allowed to intervene. Table 6 refers to nuclei produced in the receiver, *A*, figure 1, by allowing the accumulating water to run off by the cock, *k*. They were then conveyed to the condenser, *C*, about 5 or 10 minutes later, by aid of the Mariotte flask, *M*. The conduction is enormously reduced, though for positive charges in the condenser it is greater than for negative charges, showing that an excess of negative nuclei has persisted.

TABLE 6.—IONIZATION OF WATER NUCLEI AFTER 5 MIN. $a=\delta(\log s)/\delta t$.

Condenser at	Time t.	Deflection s.	Observed a.	Insulation a.	Corrected a.
volts.	min.	cm.			
+30	0	18.9	.019	−.009	.010
	1	.1			
	2	17.3			
	3	16.6			
−30	0	18.9	.005	+.002	.007
	1	.7			
	2	.5			
	3	.2			

In table 7 the data refer to nuclei which were left in the vessel *A* for about one hour after they were produced. The original ionization has all but

TABLE 7.—IONIZATION OF WATER NUCLEI AFTER 1 HOUR. $a=\delta(\log s)/\delta t$.

Condenser at	Time t.	Deflection s.	Observed a.	Insulation a.	Corrected a.
volts.	min.	cm.			
+20	0	20.0	.013	.009	.004
	1	19.3			
	2	18.8			
	3	18.3			
−20	0	26.1	.003	.001	.002
	1	26.1			
	2	25.8			
	3	25.7			

vanished; nevertheless there is still an excess of negative nuclei, as shown by the greater leakage of positive charges in the condenser. If negative nuclei had been more rapidly precipitated in the intervening hour in A, the reverse should have been the case; there should have been an excess of positive nuclei, and negative charges in the condenser should vanish more rapidly.

Tested for coronas, even after about one hour, 50,000 were left, or over $\frac{1}{3}$ of the original 10^5 to 2×10^5, a result quite out of proportion with the loss of ionization. The electrical and the condensational phenomena are thus distinctly separated.

11. *Results with an Elliott electrometer.*—For reasons which need not be stated, the electrometer of modern type in which the charge is imparted to the needle through the suspension, notwithstanding its sensitiveness and low capacity, was not adapted for further experiments. Accordingly, the data of the following table were obtained with an ordinary electrometer, with the quadrants permanently charged with a water battery. The core of the tubular condenser communicated with the needle. This adjustment was chosen because the leakage here was relatively smaller, though the high capacity of needle, jar, and condenser is unfavorable to sensitiveness. The table contains results in which the potential of the core of the condenser was altered in steps of one half. Care was taken to determine the insulation immediately before and after each measurement with the nucleated medium. The leakage is seen to be always greater at the beginning than at the end, which is the usual phenomenon of absorption and release of charge in the insulators. If any trace of radioactivity occurred it would be obscured by this phenomenon.

The results of this table may be summarized.

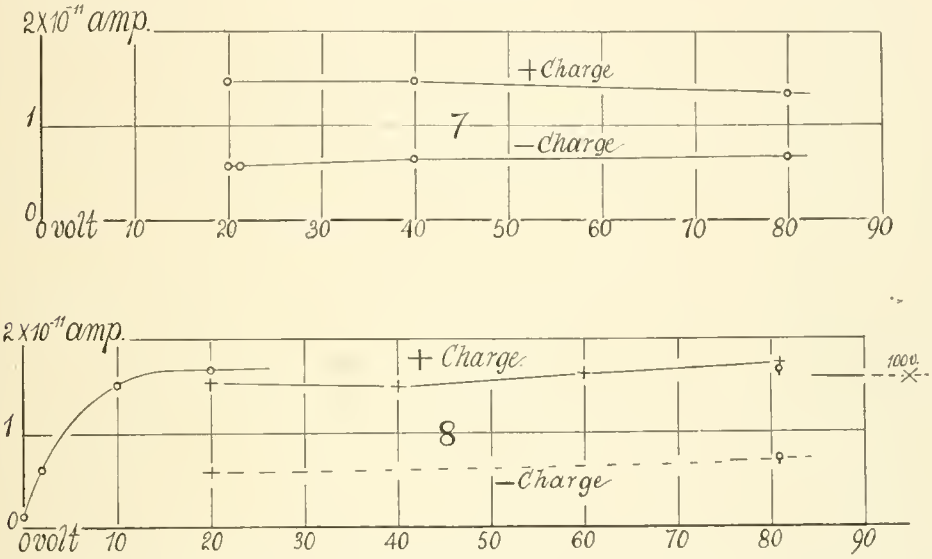
TABLE 8.—CHARGES OF WATER NUCLEI. $dV/dt=2$ LIT./MIN. CAPACITY 409 cm. DEFLECTION OF THE ELECTROMETER, s.

Electrometer charge.	Leakage ds/dt per 2^m. Before. cm.	During nucleation. cm.	After. cm.	Current $C\,(dE/dt)\times10^{11}$. amperes.
+ at 81 volts	.13	.64	.09	1.33
− at 81 volts	.17	.39	.06	.67
+ at 40 volts	.10	.67	.06	1.47
− at 40 volts	.11	.34	.05	.64
+ at 20 volts	.08	.63	.03	1.45
− at 20 volts	.06	.27	.02	.57

The ionization here is somewhat greater than the preceding, but the difference is at once referable to the gradually increasing size of the holes in the lead jet as the result of long spraying. Slight changes in V lit./min. are now of importance because of the rapid loss of the charges in the influx tube of the condenser.

Whereas the current for positive charges decreases with the potential, the current for negative charges increases; but this, too, is due to incidental reasons of the kind mentioned. Seen in the light of the results preceding and following it, the general evidence of the table is rather to the effect that the current in the condenser is constant, independent of the electromotive force when the gradient exceeds about 20 volts per radial centimeter.

These results are given in the chart, figure 7.



Figures 7, 8.—Curves Showing Radial Currents (Amperes) for Different Charges and Potentials (Volts) in the Condenser.

12. *Further data.*—A series of results quite similar to the last, but with a more sensitive electrometer, is given in the next table. As a rule, positive charges were taken in succession, though a number of incidental data accompany the table. The insulation of the electrometer was found before and after each measurement with nuclei. Having been taken on different days and not in a single sweep, the results cannot be quite coincident, because of jet differences, water pressures, etc., as already stated.

These results are summarized.

The currents are given in the chart marked figure 8. They show that above 10 volts the currents are practically constant, remembering that any change in V due to water pressure, etc., will convey the nuclei more rapidly into the condenser, and from their exceedingly rapid decay at the outset the currents will necessarily be variable. Below 10 volts the current decreases with the potential, but remains quite appreciable even when the potential is zero with the absence of charge in the condenser. The two observations made for the negative charge indicate similar relations, when taken in connection with the preceding results.

TABLE 9.—CHARGES OF WATER NUCLEI. $dV/dt = 2$ LIT./MIN. CAPACITY 409 cm. ELECTROMETER DEFLECTIONS, s.

Electrometer charge.	Leakage ds/dt per 2^m. Before. cm.	During nucleation. cm.	After. cm.	$C\,(dE/dt) \times 10^{11}$. amperes.
+at 81 volts	.21	1.88	.17	2.17
−at 80 volts	.23	.98	.19	.95
+at 81 volts	—	1.98	.22	1.74
+at 60 volts	.22	1.79	.13	1.62
+at 40 volts	.11	1.55	.04	1.48
+at 20 volts	.05	1.57	.00	1.54
−at 20 volts	.13	.68	.05	.59
+at 20 volts	.08	1.56	.02	1.51
+at 20 volts	.08	1.46	.05	1.66
+at 10 volts	.02	1.29	.00	1.51
+at 2 volts	.01	.52	.00	.61
±no charge	.00	.11	.00	.13
+at 100 volts	.16 *	.88	.12	1.59

Corona on immediate condensation: white, crimson, green, being No. 9 with about 150,000 nuclei per cm^3.

* Smaller electrometer factor.

The average number of ions in those cases where positive and negative charges were observed are again found to be slightly larger than the preceding, due to further enlargement of the holes of the jet, whereby fresher nuclei are put into the condenser.

The table states that the most advanced corona obtainable did not exceed the middle green-blue-purple type of my series,[1] throughout the whole of the work. It makes little difference whether the corona is taken instantly or a few minutes after the jet is shut off. The number of nuclei therefore is constant throughout the experiments, being about 10^5.

13. *Jets self-shattering or impinging on water.*—To make sure preliminarily that no induced radioactivity is demonstrable within the limiting potentials to be employed, the experiments of the following table 10 were devised. Here the large vertical jet (No. 9, with 18 needle holes, discharging about 8 liters per minute into the water below and violently churning it) was put in action, and the air above the water in the aspirator discharged into the condenser by the rise of level due to the jet. The table shows the insulation before and after the passage of nucleated air, for different potentials in the condenser. The data are given in centimeters of deflection per minute (ds/dt). Hence the currents are $i = ds/dt \times 2.4 \times 10^{-11}$ amperes.

[1] *Phil. Mag.* (6), III, pp. 80–91, 1902, corrected in *Am. J.*, XVI, 1903, p. 325, and in Boltzmann's *Jubelband*, p. 204, 1904. *Cf.* Chap. VI.

TABLE 10.—ABSENCE OF APPRECIABLE RADIOACTIVITY. VERTICAL JET NO. 9 IMPINGING ON WATER WITH VIOLENT CHURNING.

Leakage [1] before expt.	Condenser charge while nuclei are passing.	Leakage [1] after expt. positive charge.	Leakage [1] after expt negative charge.
.07	0 volts	.14	.23
.00	+10 "	.05	.06
.06	−10 "	.00	.01
.03	+20 "	.13	.12
.06	−20 "	.08	.02
.10	+60 "	.07	.21
.20	−60 "	.18	.09
.15	+80 "	.10	.31
.18	−80 "	.24	.07

[1] Condenser at 80 volts in first row. Positive and negative charges follow charges of same sign during passage of nuclei.

As it is the purpose of the present section to find the nucleation and the ionization of jets when shattering against a solid obstacle is avoided, the experiments were all made with jets either discharging vertically down into water or with jets impinging upon each other either vertically or horizontally.

The table shows that the insulation is, as a rule, better (smaller leakage) after than before the passage of nuclei, for potentials of the same sign, so that no induced radioactivity can be detected in comparison with the absorption and release of charges by the apparatus. The absorption phenomenon is strongly marked when the sign of the charge is changed, as in the two experiments after nucleation.

TABLE 11.—IONIZATION AND NUCLEATION OF WATER NUCLEI.

Jet.	dV/dt	Condenser at	$i \times 10^{11}$	$i \times 10^{11}$ per 2 lit./min.	Original nucleation.
	lit./min.	volts.	amperes.	amperes.	
No. 9, with 18 holes .05 cm. diam. in copper plate. Violent churning	8	+81	2.2	.55	30000
	8	−81	1.0	.25	
No. 9, with 8 finer holes in lead plate. Slight churning	2	+100	.12	.12	corona small
No. 7	3	+80	1.0	.66	30000
	4	+80	1.2	.60	
No. 3	3	+80	.8	.50	80000
	6	+80	2.4	.80	
No. 2	2	+81	—	1.33	120000
		+81	—	2.17	
		+81	—	1.74	

The ionization of the air from this turbulently discharging jet was now tested as in table 11. The coronas obtained did not go further than to correspond to about 30,000 nuclei, whereas those of the radial jet, No. 2, correspond to 10^5 or more. Hence weak ionization is to be expected, if the two occurrences go in parallel. The table (part 1) shows the positive and negative currents when 8 liters of nucleated air pass through the condenser per minute. Hence for 2 lit./min.

$$\text{at } +\ 80 \text{ volts,} \qquad i = .55 \times 10^{-11} \text{ amperes,}$$
$$\text{at } -\ 81 \text{ volts,} \qquad i = .25 \times 10^{-11} \quad \text{"}$$

giving a mean current $i = .40 \times 10^{-11}$, as compared with 1.6×10^{-11} amperes for the radial jet. Thus the mean current is about 4 times smaller, and the mean nucleation also about 4 times smaller, as nearly as can be ascertained. Therefore, the reduction of nucleation and of ionization run in parallel.

For the flat-bottomed lead jet with 8 very fine needle holes, the ionization was almost inappreciable. The current was about 10^{-12} amperes, not much exceeding the ordinary leakage of the electrometer. The corona was correspondingly small.

The next experiments, made with two capillary threads of water impinging on each other (jet No. 7), are given in the third part of the table. The different data for the mean current in case of a positive charge in the condenser and a supply of 2 lit./min. of nucleated air passing through it show that $i = .6 \times 10^{-11}$ amperes. The coronas correspond to about 20,000 or 40,000 nuclei, evidencing a relatively large ionization.

The last experiments of the table were made with the large oblique jet No. 3, and the coronas here obtained are just inferior to those of the radial jet, corresponding to about 80,000 nuclei per cubic centimeter. The positive currents are about $i = .7 \times 10^{-11}$ amperes. When $dV/dt = 3$, almost half the ions are lost in transfer.

Experiments were made at somewhat greater length with two oblique capillary threads of water shattering each other, as in jet No. 3, above. Special care was taken to *prevent* the jet from striking the walls of the vessel. As the *self-shattering* was very complete, the spray reached the water with but little churning. In spite of the small amount of water used, however, relatively many nuclei were produced, the number estimated from coronas being 40,000 per cubic centimeter.

Moreover, to keep the conditions more uniform, the water level in A, figure 1, was kept constant (efflux from k (Fig. 1) being just as large as the water coming from the spray), and the nuclei were removed by a current of air flowing through A into the condenser, C, at the rate of 2 liters per minute. The currents so obtained are relatively large as compared with the number of nuclei, which is due to the condition that the space in which the nuclei are produced is less than $\frac{1}{3}$ as large as usual above, and that therefore nuclei are fresher on entering the condenser. The mean positive and negative currents were

$$\text{at } +80 \text{ volts,} \qquad i = 1.1 \times 10^{-11} \text{ amperes,}$$
$$\text{at } -80 \text{ volts,} \qquad i = .3 \times 10^{-11} \text{ amperes,}$$

the mean, $.7 \times 10^{-11}$ amperes, being about half as large as the currents for radial jets, whereas the nucleation is deficient. The reason will presently appear (§ 14). The currents for negative charges in the condenser, moreover, are exceptionally small relatively to the positive currents.

No charge was imparted to the condenser by the spray, the current vanishing with the potential; but this also occurs at times with the radial jet.

TABLE 12.—SPRAY FOUND IN SMALL SPACE AND REMOVED BY AUXILIARY AIR CURRENT. JET NO. 3, CAPILLARY THREADS, SELF-SHATTERING.

Condenser charged to	dV/dt	$i \times 10^{11}$ observed.	Mean $i \times 10^{11}$ corrected.	ds/dt	$i \times 10^{11}$ per 2 lit./min.	Nucleation.
volts.	lit./min.	amperes.	amperes.		amperes.	
+80	2	1.03	1.14		—	40000
+80	2	1.32				
+80	2	1.19				
+80	2	1.00				
+80	2	1.16				
−80	2	·35	·30			
−80	2	·32				

TABLE 13.—SPRAY FORMED IN GRADUALLY DIMINISHING SPACE AND REMOVED BY RISING SURFACE OF WATER.

Condenser charged to	dV/dt	$i \times 10^{11}$ observed.	Mean $i \times 10^{11}$ corrected.	ds/dt	$i \times 10^{11}$ per 2 lit./min.	Nucleation.
+80	3·5	1.19	1.04	·38, ·44, ·53	.62	40000
+80	3·5	·99		·37, ·42, ·45		
−80	3·5	—	·35	—	.20	
+80	2.5	—	·72	—	·58	
+80	1.0	—	.29	—	·58	

14. *Summary of the relative degree of ionization and nucleation.*—The number of nuclei, and the electric conduction of the nucleated air, are quantities which increase and decrease together. Nuclei and ionization are produced whether the jet is shattered by a solid obstacle, by two impinging jets, or by jets impinging on a surface of water, but the efficiency of the spraying arrangement depends on the degree of comminution produced, and in this respect the jets shattered at the highest velocity by a solid obstacle are preferable. When the jet is shattered on itself or on a surface of water, the electrical current vanishes with the potential difference in the condenser, so far as can be seen; or at least is less than 5 per cent. of the constant positive current. When the

jet is shattered against a solid, the charging current, for the condenser at zero potential, is about 8 per cent. of the constant current; but it may also be absent.

The ratio of the ionization to the nucleation does not always appear as a fixed quantity; from which it follows that the mean charge per nucleus depends on incidental conditions of freshness, the nature of the jet, its impact, etc. Similarly, the ratio of positive to negative ionization does not seem to be a fixed quantity, but to vary under the same conditions. Nuclei generated in a small space are more highly charged because they can be more swiftly transferred to the condenser.

Finally, the maximum nucleation for any jet is reached when as many nuclei are produced per second as are lost in the same time. Unquestionably the air current accompanying the action of a violent jet contributes to this loss, by washing the air against the sides of the vessel and the surface of water. Hence jets with a strong single direction, even if made up of filimentary jets, produce few nuclei.

Finally, the reason for the unique efficiency in the capillary oblique jet was specially verified. Supposing that the high ionization relatively to the nucleation in this case is due to keeping the water level near the jet and expelling the nuclei by an auxiliary air current from a small volume, I made the following experiments in which the nuclei were discharged by a rising surface of water by aid of the Mariotte flask. Table 13 shows that on successive half minutes the currents ds/dt increase rapidly, as was supposed. Moreover, when referred to an efflux of 2 liters per minute, the amperes are now actually of the low order corresponding to the nucleation of the jet.

The effect of different volumes is also seen from the table, which proves that proportionality is roughly admissible. This also follows necessarily from the equation of the phenomenon given elsewhere (*cf.* § 18), and has been carefully verified for phosphorus.

15. *Spontaneous time loss of nuclei.*—The following table (14) shows the spontaneous loss of nuclei in the lapse of time. The nuclei were produced in the receiver in the usual way, and their number was then determined by the condensation produced after a stated interval. The approximate number or order of the corona in my series is nevertheless somewhat difficult to determine, and the number of nuclei estimated therefrom not quite definite. As this number is an exponent, arithmetical progression indicates geometric progression in the number of nuclei.

The radial jet, No. 2, shattering itself against the sides of the vessel is strongest as a nuclei producer, and the large oblique jet, No. 3, considerably below it in efficiency. The capillary oblique jet, No. 3, is remarkably efficient relatively to the quantity of water used. The vertical large copper jet, No. 9, used in tables 10 and 11, is a very poor producer of nuclei, though using about 8 liters of water per minute and in spite of the turbulent churning of the pool below.

TABLE 14.—LOSS OF WATER NUCLEI IN LAPSE OF TIME. ESTIMATED.

Jet.	Lapse of time.	Corona.	Nucleation.
	min.		
No. 2. Radial.	·3	w br b g	120000
	·3	w r g	140000
	6.0	g br b r	100000
	10.0	w r | g	75000
	·3	w br b g	120000
No. 3. Large.[1]	·3	g br b r	100000
	·3	gy br b r	90000
	6.0	y′ c g	70000
	·3	gy br b	90000
	10.0	w c g	65000
	·3	w r b g	75000
	·3	y′ r g	80000
No. 3. Capillary.	·3	gy r b r	50000
	·3	gy br b r	45000
	10.0	gy br b r	45000

[1] Note that the second jet gradually loses efficiency.

16. *Effect of condensation on ionization.*—The following table shows the effect of precipitation on the ionization of the water nuclei. The original current (without condensation) is given both for positive and for negative charges. The condensation was produced by exhaustion immediately after the jet was shut off and but a few minutes allowed for subsidence of the fog. Only a small number of nuclei relatively to the total number therefore can have been removed. On the other hand, however, the original ionization has vanished as the result of condensation, for the residual currents are below those corresponding to the normal leakage of the condenser and electrometer, and are thus mere errors. One may note that both the positive and the negative ionization is completely removed by condensation, even though subsidence of fog particles has been all but excluded.

TABLE 15.—IONIZATION OF WATER NUCLEI AFTER PARTIAL PRECIPITATION.

Condenser charge at	dV/dt	No. of precipitations.	$i \times 10^{11}$ corrected.	Electrometer leakage $i \times 10^{11}$.
volts.	lit./min.		amperes.	amperes.
+80	2	0	1.34	.11
+80	1.5	1	.03	.07
−80	2	0	.77	.03
−80	1	1	.06	.06
−80	2	1	.03	.12

Another peculiarity may here be referred to: when the radial jet is very active it is capable of charging the neutral condenser. This, however, is not usually the case with a jet striking water. The following table, in which s denotes the galvanometer deflection, shows that the radial jet, when shattered on a rigid obstacle, does not always convey charge.

TABLE 16.—CONDENSER[1] CHARGED BY RADIAL JET. $dV/dt=2$ lit./min.

Time, =	0	1^m	2^m	3^m	4^m	5^m	6^m
Charge, $s=$	—	.00	.01	+.00	+.02	.04	—
Leakage, $s=$	.01	—	—	—	—	.00	.00
				$dV/dt=4.5$ lit./min.			
Charge, $s=$	—	.00	−.01	−.01	—		
Leakage, $s=$	.00	—	—	—	.00		

[1] Combined capacity 409 cm.; 5 volts per scale part.

In these experiments non-symmetrical charge was not detected when the nuclei from the radial jet passed through the uncharged and insulated condenser. This was even true when the air current carrying the nuclei was increased to nearly 5 liters per minute. Reasons for this diversity of behavior have yet to be sought.

17. *Effective condenser length.*—It is finally desirable to ascertain whether the charges of water nuclei are actually lost to a few per cent. in the first few centimeters of the condenser, very near the influx tube. A condenser was therefore constructed the length of which could be varied by placing earthed tubes, $2r_2=2.1$ cm. in diameter and of different lengths, $l=60$, 30, and 15 cms., around a fixed charged insulated core, $2r_1=.64$ cm., concentrically, with the usual precautions.

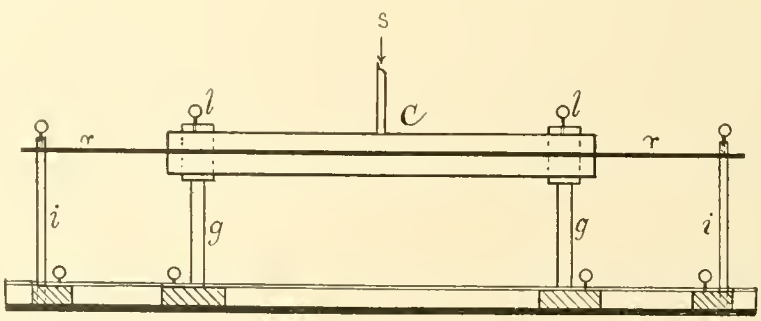


FIGURE 9.—TUBE CONDENSER WITH SLIDING AND REMOVABLE OUTER COATING.

Figure 9 shows the apparatus where r is the inner and C the outer coating of the condenser, the latter held in the sleeves, ll. The insulators and the metallic supports are capable of sliding to and fro in the base plate and of being clamped in any position. Influx of nuclei occurs at *s*. To change *C*, the sleeves *ll* are loosened and the rod *rr* removed, after which the tube *C* may be slid off and another inserted. Set screws and clamp screws complete the adjustment as shown in the figure.

Table 17 shows the results in which the insulation of the condenser was determined before and after each measurement with the nucleated medium. The condenser lengths, 60 and 15 cms., are inserted as a sufficient contrast.

TABLE 17.—EFFECT OF LENGTH OF TUBULAR CONDENSER. $dV/dt=1.9$ LIT./MIN. $A=3.5$ VOLTS/cm. $C=409/9\times 10^{11}$ FARADS.

Length	Condenser charge at	Leakage. *ds/dt*, Observed. Before.	During.*	After.	Corrected $i\times 10^{11}$.
cm.	volts.	cm./min.	cm./min.	cm./min.	amperes.
60	+80	.02	.39	.00	1.07
			.40		
			.43		
			.45		
15	+80	.05	.37	.00	1.12
			.42		
			.47		
			.52		
15	+80	.00	.44	.02	1.20
			.45		
			.47		
			.58		
15	−80	.03	.25	.00	.62
			.24		
			.26		
			.30		

* During the passage of nucleated air through condenser.

It is seen that the currents are certainly quite as large, *cæt. par.*, when the length of the tube condenser is 15 as when it is 60 cm. It is actually larger at 15 cms., due to the gradual enlargement of the needle holes[1] in the lead jet, whereby fresher nuclei are conveyed into the condenser. The currents for positive and for negative charges have the usual relation to each other.

The table shows another interesting fact, already pointed out above, that the current, *ds/dt* (per min.), increases as the water level in the receiver rises, or as the discharge into the condenser is fresher. One naturally inquires what the maximum charge of each nucleus would be if there were no conveyance tube.

[1] The fine holes clog with lead hydrate when the jet is left standing in a damp atmosphere, and the obstruction is gradually removed by the friction of the water. Old jets long unused therefore show small electrical currents as compared with new jets.

The successive values of the table (one minute apart) correspond on the average to about 16 per cent. per minute. In the present installation this jet was unable to charge the condenser, the charging current being less than 10^{-12} amperes, about of the same order as the leakage.

One may conclude, therefore, that the loss of charge per minute, *i. e.*, the electrical current radially traversing the condenser, is practically independent of its length if the latter exceeds a few centimeters, for the air current and width given. All but a few per cent. of the charge are lost in the first few centimeters ahead of the influx tube of the condenser. The experiments are thus in keeping with the surmise of the preceding paragraphs.

SUMMARY AND INFERENCES.

18. *Working hypothesis.*—In conclusion a brief summary of the working hypothesis from which most of my work has proceeded may be added for reference.

Let the ions be regarded as charged nuclei, and let there be an average of q electrons per nucleus. Let the loss of ions be due merely to absorption of the charges at the boundary of the region. This is virtually stating that the loss is as the first power of the number n, per cubic centimeter. Whether the charge travels with the nucleus, or whether it travels from nucleus to nucleus along a highway of nuclei, as it were, is left open, but the charges are lost at the boundary at a more rapid rate than the nuclei.

To fix the ideas, let a tube condenser of radii $r_2 > r_1$, and length, l, be given, and let v (cm./sec.) be the velocity of the air current bearing charged nuclei longitudinally through the condenser. If V is the volume of this air in liter/min. entering the condenser at one end, $\pi\,(r_2^2 - r_1^2)\,v = 16.7\ V$.

The loss of nuclear charges is then due to two causes: (1) These charges have a specific velocity, k (absorption velocity in a given cardinal direction) in the absence of the electric field. Charges are lost in pairs by this non-directed motion without producing current. (2) The nuclei have a second velocity, U', in the same direction per electron carried and per volt/cm. of the field. Hence the number of nuclei, n, at the section l cm. from the influx end, where $n = n_0$, is given per unit of length by

$$n = n_0\,\varepsilon^{-2Kl/v(r_2+r_1)} = n_0 \varepsilon^{-a} \quad . \; . \; . \; (1)$$

where $K = k + qEU'/(r_2 - r_1)$ and $\alpha = .377\ lK\,(r_2 + r_1)\,/V$.

The radial current at the same section, if the potential difference between the surfaces r_2 and r_1 of the tube condenser is E, will not depend on k, but on U', so that

$$-di = 2\pi\,(r_2 + r_1)\,neU'q^2\,(E/(r_2 - r_1))\,dl$$

or eventually

$$-C\ dE/dt = \frac{16.7\ Vn_0 eq^2(l - \varepsilon^{-a})}{q + k/(U'E/(r_2 - r_1))} \; . \; . \; . \; (2)$$

where C is the capacity of the condenser and e the charge of one electron, while q such charges travel per nucleus.

Experiment shows that the currents are of about the same order when charged water nuclei from an intense high-pressure jet and when charged phosphorus nuclei are passing longitudinally through the condenser. But as the number of water nuclei as tested by coronas are, even in the condensation chamber, not above 10^5 per cubic centimeter, while the number of phosphorus nuclei may reach 10^7, the charge q in electrons per nucleus is large for water nuclei and small for phosphorus. Similarly one may expect the water nucleus derived by a mechanical process to be larger than the initial phosphorus nucleus derived chemically, so that k is larger in the latter case.

Hence it is assumed that in case of water nuclei, k is negligible in comparison with $qEU'/(r_2 - r_1)$ and equation (2) becomes, if $qU' = U$

$$-C\, dE/dt = 16.7\ Vn_0\,(eq)\ \left(1 - \varepsilon^{-.377\, l(r_2+r_1)UE/V(r_2-r_1)}\right).$$

This equation, which fits the phenomena very well, predicts saturation as the exponent is essentially dependent on E.

On the other hand, in case of phosphorus nuclei, k is large in comparison with $qEU'/(r_2 - r_1)$, for here a single electron travels with many nuclei. The exponential term in (2) vanishes or

$$-C\, dE/dt = 16.7\ Vn_0 cq^2 EU'/k\,(r_2 - r_1)$$

which is virtually Ohm's law.

An endeavor has thus been made to explain the two types of conduction in question, the charged water nucleus type and the phosphorus nucleus type, by a simple self-contained hypothesis. I have not, however, been able to complete the numerical details to my satisfaction, and will therefore leave the subject here without further comment.

19. *Charge and conduction.*—The data have shown that positive as well as negative charges are dissipated by water nuclei, immediately after they have been produced, and that the ionization, if it may be so called, is quite of the order of that of phosphorus, while the nucleation is much smaller. After being stored but a few minutes, the nucleation loses all but a few per cent. of this property of conduction, behaving in this respect again like phosphorus nuclei. The number of nuclei does not appreciably vary in the same time. The character of the ionization (whether positive or negative nuclei are in excess) remains intact so long as it can be observed. Hence the large initial and the eventual very small conduction (a few per cent. of the original value) may be regarded as two successive phases of a single continuous phenomenon, either of charge or ionization or conduction. It seems to me therefore that it is not necessary to distinguish the initial charges from the initial ionization. The experiment as a whole shows an attenuation of the Lenard effect, continuously through infinite time. One is at liberty to refer the conduction either to charged nuclei or to ionized nuclei unless some distinctive definition is adopted. Both occurrences are similarly reduced. The present case of river water is one in which there is an excess of negative over positive nuclei. In other cases (pure water) the reverse may be the case, or, again, there may be an absence of an excess of

either sign. If the nuclei were without charges, however, the medium would not conduct. In a condenser, positive or negative charges are sooner dissipated according as there is excess of negative or positive nuclei in the medium, respectively.

20. *Comparison of phosphorus and water nuclei.*—Between phosphorus and water nuclei there is in the first place the essential difference that whereas the current in the first case obeys Ohm's law, roughly, it does not do so in the second, being more and more independent of the electromotive force as E increases above about 15 volts per cm. Similarly, the coronas for water nuclei usually terminate with the middle g-b-p type, whereas in case of phosphorus they go to indefinitely higher orders, beyond the first in the series. Parallel to this there may run a difference in the size of nuclei. The inference is warranted that phosphorus nuclei are small as compared with water nuclei, inasmuch as the latter owe their origin to mechanical conditions, while the phosphorus nuclei arise under molecular conditions and molecular dimensions. As the observed electric currents are about of the same order in both cases, it follows that the charges per nucleus are very much larger for water nuclei than for phosphorus. If water nuclei could be examined immediately after production, *i. e.*, in the same degree of freshness as is customary for the phosphorus nuclei, the contrast would be enormous.

In both cases, however, whenever ionization and nucleation are associated phenomena, the number of ions generated varies directly with the concomitant number of nuclei.

In other respects there is great similarity in the behavior of the two types of nuclei. The enormous charges of ionizations at the beginning vanish to a residuum of a few per cent. in a few minutes if confined by a receptacle, while the nuclei are not affected either as to number or condensational properties by the presence or absence of the primitive charge. It is not unreasonable to suspect, therefore, that the water nucleus, like the phosphorus nucleus, may be the permanent residue produced by the expulsion of the electrons representing the ionization: for whenever nucleation and ionization arise in a common source, any increment of the former is accompanied by a corresponding increment of the latter.

CHAPTER III.

PRELIMINARY SURVEY OF THE APERTURES OF CORONAS, IN RELATION TO THE NUMBER OF NUCLEI AND THEIR SIZES.

1. *Introductory.*—Throughout my earlier work with coronas, I have relied chiefly upon the color sequences, and have taken the data for numbers and sizes of cloud particles (a fixed degree of supersaturation presupposed) from the tables given elsewhere.[1] When apertures were measured this was done chiefly for the identification of the series to which the corona belongs. There is no doubt, however, that an expression for the diameters of particles in terms of the aperture of the coronas would be a great and immediate convenience, particularly as facility in using the color sequences is apt to be lost, unless one is at work with them continually. Apart from this, the colors represent steps of progress, while the apertures should be continuously, even if irregularly, variable. The purpose is then to find under what conditions the discrepancies of aperture may be reduced to a minimum.

If the supersaturation is constant throughout, the diameters of cloud particles and their distance apart will in general be proportional quantities. Let m be the grammes of water precipitated, n the number of particles per cubic centimeter, $D=n^{-1/3}$ their distance apart, d the diameter of each, s the aperture of the corona. If, therefore, for normal coronas $d=a/s$, where a is a constant found by purely optical experiments,

$$n=(6m/\pi a^3)\, s^3=(6m/\pi)/d^3=1/D^3, \text{ and } d=D(\pi/6m)^{1/3}.$$

But it is doubtful if these equations are true even for normal coronas; they must certainly be a very crude approximation for coronas of the higher orders, where d and D are possibly both implicated in producing coronal effects. If one builds up a system of glass plates each sprinkled with lycopodium particles, the diffraction pattern, which is finely multi-annular for a single plate, is a mere blur for 10 plates placed within a linear foot, for instance, without changing the aperture appreciably. If the source of light and the eye are both distant, the coronas gradually lose sharpness and soon cease to be measurable as the number of plates increases. This indicates that greater uniformity of distribution and equality of diameter must be met with in case of cloud particles, but it leaves the question open whether the distance apart of particles is not from the outset a consideration.

[1] *Am. Journ. of Science* (4), XIII, p. 81, 1902; *Phil. Mag.* (6), IV, p. 26, 1902; cf. *Structure of the Nucleus*, Smithsonian Contributions, 1903, Chapter III.

What is further menacing is the distortion produced by spherical and cylindrical vessels, the surfaces of which are rarely quite concentric. In my work with globes, I assumed that if the annuli showed no distortion and were small in aperture as compared with the aperture of the globe, distortion could be neglected. It is questionable, however, if this observation is vouched for, since the apertures of coronas are peculiarly sensitive to refraction, particularly when the distances of eye and source from the receiver are purposely chosen large.

Again, the quantity m is dependent on temperature. It is necessary therefore to refer coronas to a standard temperature as well as to a given degree of supersaturation, and the correction is important if the coronas are to be used in estimating the number of particles.

Finally, the ratio of densities before and after exhaustion is a seriously difficult datum to determine, for it depends on the degree to which adiabatic conditions have been attained. It is here that the work is liable to be discrepant. Hence a determination of apertures has an ulterior value, for it is not improbable that the two series of results will *mutually interpret each other*. The present chapter bears out this surmise, though it is merely to be regarded as a rough test of my earlier results (*l. c.*). An independent survey is made in Chapter VI with plate-glass vessels.

2. *Apparatus and preliminary results.*—The following charts contain a preliminary survey of the sequence of coronas, their apertures, and the number of particles of specified diameter encountered. The data for diameter and number, d and n, are taken from my work on successive exhaustion (*l. c.*), where the experiments are largely non-optical, and they are compared with the corresponding data d' and n' which follow from measurements of aperture. The eye and source of light are distant 1 and 3 meters, respectively, from the condensation chamber between them. This was here a long cylindrical vessel of as clear glass as possible, 50 cm. long and 13 cm. in diameter. The observations were made parallel to the axis, absence of distortion being assumed for the axial plane, an assumption which was justified by trial comparisons with plate-glass apparatus, though the latter was not quite large enough for the complete survey. The method of work was otherwise the same as that described in the earlier papers.

The results of the work may be given without tables in the accompanying charts, figures 1, 2, 4, 5, 8, 9, in which the old results for d and n (computed from successive exhaustions) are laid off horizontally, the new results d' and n', computed (as stated) from the observed aperture, vertically. The discrepancy of the two sets of data is enormous, and the curves all show sustained periodicity. All measurements of aperture, s, are made to the inner edge of the red ring, and show the diameter of the central disc.

3. *Diameter of cloud particle.*—The variations of d and d' are on the average $\delta d = 1.4\delta d'$, from curve 4, and $\delta d = 1.6\delta d'$ from curve 5. In other words, the diameters obtained for coronas by computation from the conditions of suc-

cessive exhaustion are about 1.5 times larger than the same data estimated directly from the apertures of the coronas.

Moreover, the new values of diameter d' show a curious periodicity which must be peculiar to them, since the old values from the manner in which they

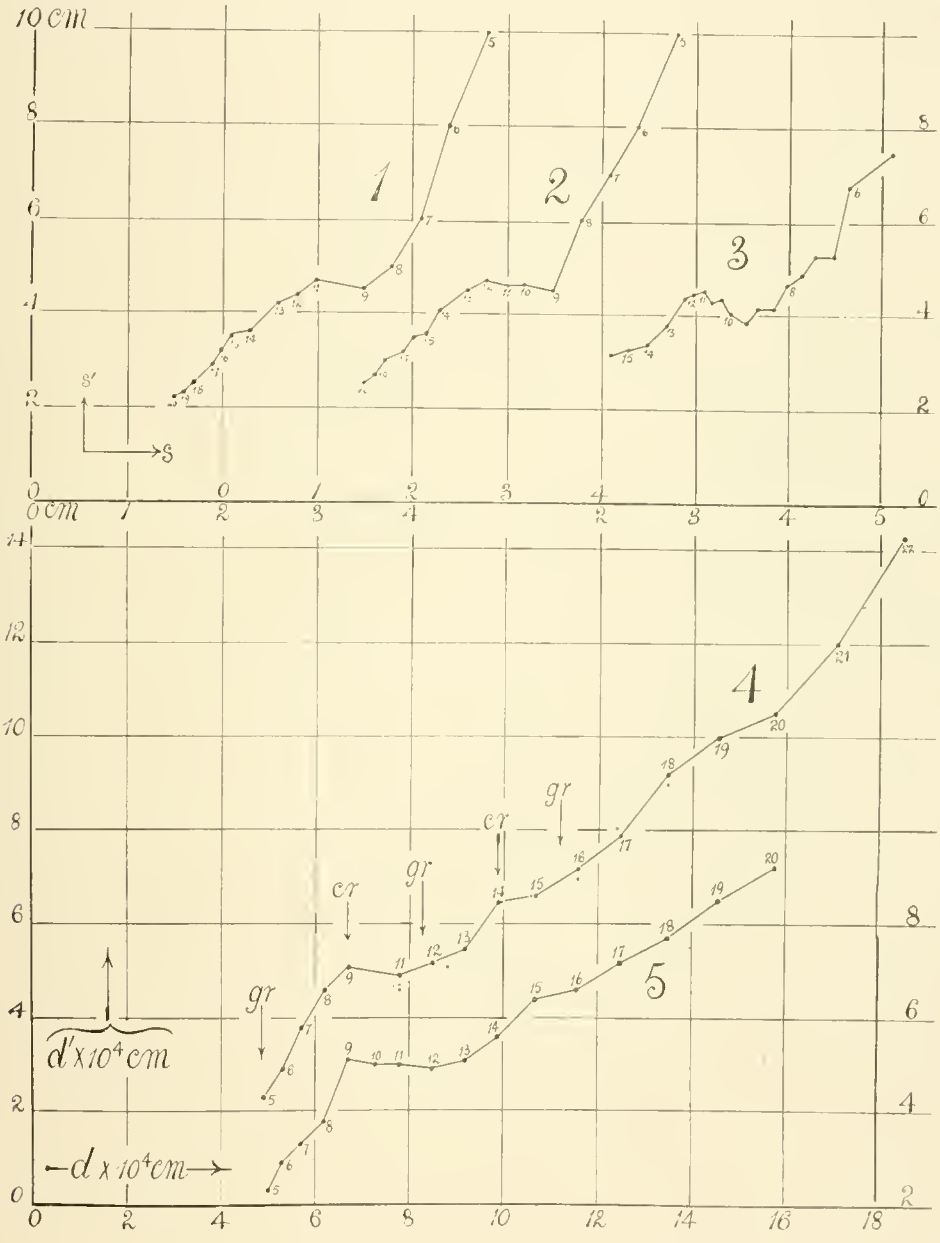


CHART I.—CURVES 1 AND 2, RELATIONS OF APERTURES COMPUTED FROM SUCCESSIVE EXHAUSTIONS (s), AND DIRECTLY MEASURED (s'). LONG CYLINDRICAL RECEIVER, 13 CM. IN DIAMETER. CURVE 3, THE SAME FOR PLATE-GLASS APPARATUS 20 CM. DEEP. CORONAS HERE DIFFICULT TO PLACE.

CURVES 4 AND 5, RELATION OF DIAMETER OF FOG PARTICLE COMPUTED FROM SUCCESSIVE EXHAUSTIONS (d), AND FROM MEASUREMENTS OF APERTURE (d'), BOTH GIVEN IN CENTIMETERS. LONG CYLINDRICAL RECEIVER. THE TYPES OF CORONAS ARE MARKED *gr* (GREEN CENTERED), *cr* (WHITE-CRIMSON CENTERED). CURVE 5 DROPPED .0002 CM. SMALL DOTS REFER TO A SPECIAL SERIES.

were obtained (geometric progression) cannot be periodic. There is accelerated increase of diameter toward the crimson types, Nos. 9 and 14, and a falling off which may even be a retrogression toward the green types, Nos. 4–5, 11–12, 15–16, these being respectively the crests and troughs of the wave. The

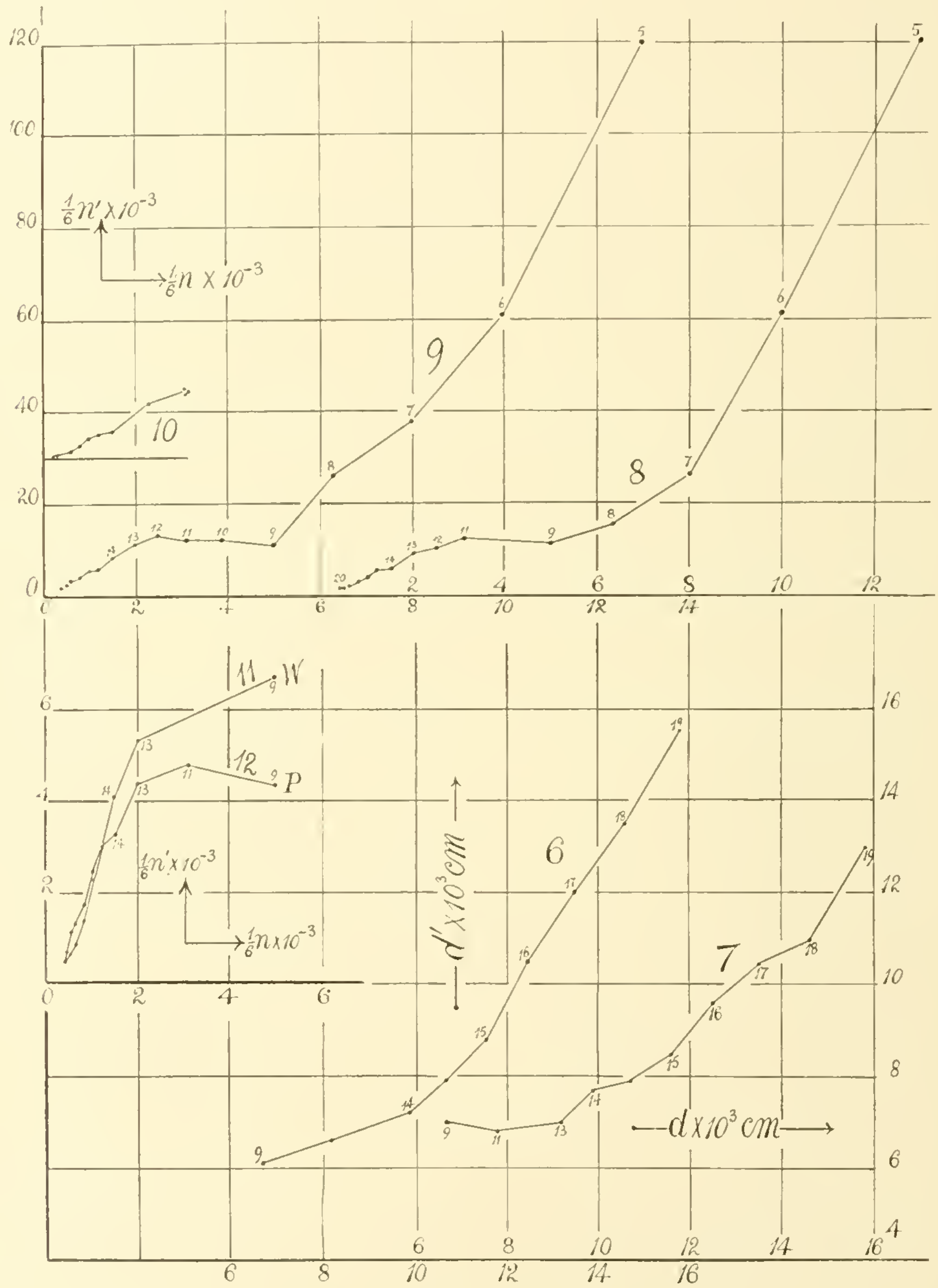


CHART 2.—CURVES 8, 9, 10, RATIOS OF NUCLEATION COMPUTED FROM SUCCESSIVE EXHAUSTIONS (n PARTICLES PER CUB. CM.), AND FROM MEASURED APERTURES (n'). LONG CYLINDRICAL RECEIVER.

CURVES 11 AND 12, THE SAME FOR ANOTHER CYLINDRICAL RECEIVER, 20 CM. DEEP. CURVE 11 REFERS TO WATER NUCLEI, CURVE 12 TO PHOSPHORUS NUCLEI.

CURVES 6 AND 7, CORRESPONDING DIAMETERS OF FOG PARTICLES IN CENTIMETERS.

undulation continues even beyond this, but it is then difficult to identify it, as the annuli become crowded into the normal coronas. The results are similar in all the curves. In other data obtained during experiments with jets in Chapter II, §§ 4, 5, 17, and given in the present figures 6, 7, 11, 12, the same undulatory line is encountered both for phosphorus and for water nuclei, with maxima at the 9th and 14th coronas. Here a different vessel (aspirator 32 cm. high, 22 cm. in diameter) was used, and the ratio, $\delta d = 1.3 \delta d'$, is distinctly smaller for this case, showing the marked influence of distortion due to the vessel. The same ratio (1.3) will be adduced below in connection with the preliminary experiments with plate-glass apparatus.

4. *Nucleation.*—Since nd^3 is constant, remarks of the same general character may be made for the nucleation, n, except that the discrepancy will be reciprocal in character and enormously exaggerated. If on the average $d = 1.5d'$, $n' = 3.4n$; if $d = 1.3d'$, $n' = 2.2n$, but the undulations have now become so sweeping that a ratio can only be inferred for the small coronas.

5. *Cause of periodicity.*—If one inquires into the cause of the periodic discrepancies, it appears that the crimson coronas are too small or else the green coronas too large, for the data computed from exhaustions cannot be periodic. The former being white-centered with a diffuse red margin, it is impossible to mistake the outside edge of the first ring for the inside edge. The blue-green coronas, however, show a uniformly colored disc, and here the first ring may be of the same color as the disc, and the corona would then be measured to the outside margin of the first ring. From this point of view only the crimson coronas are adapted for measurement, and both curves would then give $d = 1.3d$, and $n' = 2.2n$. Since the curves actually give evidence of diminishing aperture while the droplets certainly decrease in size, this explanation is plausible, though it does not agree well with the evidence from normal coronas. The red and crimson coronas are the only ones which retain the white center, and the phenomenon may in so far be regarded as similar to the case of normal coronas.

6. *Effect of temperature.*—The explanation of the discrepancy between d and d' (computed from exhaustions and measured from apertures, respectively) reduces in the most favorable case to $d = 1.3d'$, and for this two explanations must be examined. Supposing that one does not inadvertently measure into a ring, the value of m which enters into the computation of d is very variable with temperature. For $\delta p = 17$ cm., for instance,

at 10°,	$m = 3.7 \times 10^{-6}$	grams per cub. cm.
20°,	4.6×10^{-6}	" " " "
30°,	5.7×10^{-6}	" " " "

Since d varies as $m^{1/3}$, for the same nucleation the values of d at 10°, 20°, 30°, will be in the ratio of 56, 60, 64, respectively, and the coronas will be in the same degree smaller. Per degree between 20° and 30° this amounts to about .8 per cent. of the value at 20°. Hence to bring the values of d computed from successive exhaustions into coincidence with the data computed from apertures would require a temperature excess of nearly 30°, which is out of the question.

7. *Pressure decrement.*—As none of the explanations are satisfactory, light of a different character may be thrown upon the discrepancy by computing by the approximate method of the earlier memoirs the density ratio, y', of the gas after and before exhaustion, corresponding to the observed values, s'. Since if n is the nucleation, z the order of the corona in a geometric series, b the coefficient of time loss, t the time interval between exhaustions,

$$\log n = z\,(1 + bt)\log y,$$

the equation corresponding to a different exhaustion ratio would be

$$\log n' = z\,(1 + bt)\log y'$$

if the same corona, z, and time interval, t, is implied.

Hence $\log n/\log n' = \log y/\log y'$, while $n = (6m/\pi a^3)\,s^3 = As^3$. Therefore, $\log y'/\log y = (\log A + 3\log s')/(\log A + 3\log s)$.

The computed values $s = a\sqrt[3]{n\pi/6m}$ are given and in the chart, figures 1 and 2. From the latter for $s = 5.0$, $s' = 8.0$ to 9.0 cm. From the earlier memoir,[1] the value computed for y was .819. Hence

$$s' = 8, \qquad y' = .807,$$
$$s' = 9, \qquad y' = .804,$$

whereas $y = .819$ was the value computed in my work on coronas for the exhaustion 76 − 58 cm.

Since, roughly, $y = (p/p_0)^{1/\gamma}$, where $p = 76$ and $\gamma = 1.4$, the following values of δp obtain:

$s = 5.0$ cm.,	$\delta p = 18.0$ cm.
$s' = 8.0$	19.1
$s' = 9.0$	19.4

Thus if the pressure decrement on exhaustion had been taken 1 cm. higher than the observed value, the apertures computed from successive exhaustions in the former memoir would agree with the average apertures directly measured in the present paper. Observationally this is out of the question, but it is nevertheless difficult to know just what pressure is effective in the adiabatically cooled receiver (cf. *Structure of the Nucleus* pp. 35, 38), since neither the isothermal nor the adiabatic conditions will rigorously suffice. The memoir shows that isothermally $y = .764$; adiabatically $y = .825$; adiabatically with allowance for condensed water $y = .819$, as already specified. The aperture data demand $y = .805$, which is even nearer to the isothermal y than the value taken.

Incidentally one may note the precision with which y must be entered or the pressure difference determined, if the observations are to be sufficiently close to admit of a computation of d and n. In other words, it is probable that the ratio y may be determined with greater accuracy from the successive aper-

[1] *Structure of the Nucleus*, Chapters III and IV.

tures as a whole, notwithstanding their periodic character, than by direct measurement. This is what I meant by stating that the two sets of observations would probably sustain each other, for nobody would be justified in using the apertures of abnormal coronas, unless such use was suggested and guided by independent evidence. The subject will be resumed in Chapter VI, and treated from a point of view different from the present, which is merely tentative.

8. *Summary.*—The result of this paper is then favorable to the use of the apertures of coronas in place of the colors of the annuli, for estimating the number of particles corresponding to a given degree of supersaturation at a given temperature. Full allowance must, however, be made for the occurrence of periodic variations of aperture in relation to the diameter of the fog particles; in other words, a given aperture is only of value when qualified by the type of corona (whether of the crimson or green order) to which the aperture belongs. Thus it will not in any case be possible to dispense completely with the color pattern. It was with the object of finding these corrections systematically that I began a series of experiments (Chapter VI) with new forms of plate-glass apparatus, and I shall there refer to other developments. Homogeneous light, though in many respects desirable, gives effects so faint as to be useless in practice.

With the above data I am able to make an independent estimate of the number of particles in the saturated phosphorus emanation. The number found for the first fog of the series was (*Phil. Mag.* (6), IV, pp. 25–26, 1902) $n=6\times 83{,}000$; since $n'=2.2n$, $n'=6\times 183{,}000$ particles per cub. cm. Now the density ratio before and after exhaustion is y, so that $1-y$ is the volume of saturated emanation added. As this has passed directly and slowly over excess of phosphorus, it must be very nearly saturated, becoming diluted on mixture with the dust-free air of the receiver. Hence, if n_0 particles per cub. cm. correspond to saturation, $n\ (1-y)\ =\ n_0=6\times 183{,}000$; or $n_0=10^6\times 6$. There must therefore be at least 6 million nuclei [1] per cub. cm. of the air in contact with a surface of phosphorus. The value following from my electrometer work was $n_0=2\times 10^6$. The two methods are absolutely distinct, but lead to data of the same order. It is because of the general reasonableness of the data which have followed from my simple hypothesis throughout a very wide territory of observation that I have felt bound to adhere to it.

PLATE-GLASS APPARATUS.

9. *Description.* To test the results just adduced, the apparatus shown in Chapter VI, figure 1, and in Chapter VII, figure 1*a*, was constructed. The frame, 20 cm. deep, 35 cm. long, 27 cm. high, was of wood, nicely joined, and covered within and without with a mixture of burgundy pitch and beeswax while hot. The front and rear faces are of 1/4-inch plate-glass, cemented on by the same resinous mixture, and further held in place by the wooden clamps,

[1] The factor 6 is introduced in conformity with the work of Chapter VI.

secured by the brass bolts at their ends (see Chapter VII). F is the filtering attachment with a cock, E the exhausting attachment, P the nucleator. Thermometers show the temperature both of the air within the chamber and of the water at its bottom. The goniometer is in front and the source of light in the rear of the apparatus, and the exhaustions are made in the way frequently described in these memoirs.

In the preliminary results, $\delta p = 4.5$ cm. was the pressure decrement on exhaustion, $t = 23°$, the temperature of the saturated air and water. The eye and the light are at distances 85 and 235 cm. from the central plane of the apparatus. Since s_0 for lycopodium is by experiment .75 cm. and $d_0 = .0032$ cm., $a = d_0 s_0 = .0024$. Hence at 20° $d = .0024/s$ and $n = 6ms^3/\pi a^3$.

The results, s and s', are constructed in the chart, figure 3, and show the same general character as the results already discussed. Moreover, since $s' = 1.3s$, the two sets of data are more nearly in correspondence here than was the case with the cylinder above. Definite results of this character for higher values of δp will presently be given (Chapter VI), after a few incidental questions have been disposed of.

CHAPTER IV.

ON THE NUMBERS OF NUCLEI PRODUCED BY SHAKING DIFFERENT LIQUIDS AND ON ALLIED DATA.

1. *Explanation.*—In my report on the nucleus,[1] I showed that the number produced in a given mode of comminution was least in pure water, greater in dilute organic solutions, and still greater in dilute inorganic solutions, all of the same strength. Results were also given for other solvents than water, in particular for benzol; but I was unable to reduce the data to the same scale as for aqueous solvents, as the data needed for the reductions were not at hand. I have since found that the method of Wilson and Thomson [2] lends itself to benzol, and have therefore computed the data over again, as shown in table 1.

TABLE 1.—NUMBERS OF NUCLEI PRODUCED BY VIGOROUSLY SHAKING DIFFERENT SOLUTIONS IN THE SAME MANNER. CONCENTRATION 1 %.

Solvent.	Solute.	Number of nuclei per cub. cm.
Water	(Pure water)	130
"	Sucrose	
"	Glucose	
"	Glycerin	630
"	Urea	
"	Tartaric Acid	
"	Na_2SO_4	
"	K_2SO_4	
"	Alum	
"	$CaCl_2$, $FeCl_3$	
"	NaCl, HCl	
"	$Ca2NO_3$	1300
"	$H_4N\ NO_3$	
"	$Al3NO_3$	
"	$Fe3NO_3$	
"	Na_3PO_4	
Benzol	Naphthalene	3500
Benzol	Paraffine	5000

2. *Data.*—The pressure reduction used to effect the condensations was throughout $\delta p = 16$ cm. Hence at about 20° the adiabatic fall of temperature in case of a benzol-air medium should be as far as $-10.2°$, the rise of temperature

[1] *Smithsonian Contributions to Knowledge*, No. 1373, Chap. V, 1903.
[2] *Phil. Mag.* (5), XLVI, p. 538, 1898.

thereafter (due to condensed liquid) to 11.3°, and consequently the liquid benzol precipitated per cubic centimeter $m=30.4\times10^{-6}$ grams. The goniometer factor was $a=.0031=ds$, being the product of the diameter d of the fog particle and the aperture s of the corona. Hence the number of nuclei per cubic centimeter is finally $n=1.95\ (10s)^3$, all the coronas in question being normal, excessively intense and brilliant.

This may be compared with water. The corresponding temperature reduction of the water-air medium is to $-7.6°$, the rise of temperature due to the ensuing condensation as far as 9.5°, so that $m=4.5\times10^{-6}$ grams per cubic centimeter almost 7 times smaller than the corresponding datum for benzol. When the same goniometer as above is used, therefore, $n=.29\ (10s)^3$.

The curious result thus appears that the number of nuclei produced by a definite amount of shaking is least for water, about 5 times greater for dilute organic solutions in water, about 10 times greater for dilute inorganic solutions in water, and about 30 to 40 times greater for dilute solutions of non-conductors like naphthalene and paraffine in benzol. It is difficult to even conjecture a reason for this behavior.

3. *Coronas in general.*—The coronas in benzol for the above pressure differences, δp, are all normal, even if nucleation from sulphur, phosphorus, etc., is introduced. From the slow diffusion of the vapor they soon become distorted during successive exhaustions unless the vessel is shaken between them. It is interesting to show, however, that in spite of the normal coronas the high initial nucleation is fully accounted for. To do this I shall select a series of observations for coronas in benzol vapor at random (*l. c.*, p. 56). Sulphur nuclei were used and the vessel shaken between observations. The table gives the results.

TABLE 2.—CORONAS IN BENZOL VAPOR. SULPHUR NUCLEI. $\delta p=18$ cm. $n=6m/\pi d^3$. $m=33\times10^{-6}$g. Per cub. cm. $d=.00144/s$.

Exhaustion No.	Observed $d\times10^3$.	Computed $d\times10^3$.	Computed n.
0	Fog	.2	6800000
1	"	.3	3200000
2	"	.4	1400000
3	"	.5	610000
4	"	.6	270000
5	.8	.8	120000
6	1.0	1.1	52000
7	1.2	1.4	23000
8	1.8	1.8	10000
9	2.6	2.4	4400
10	3.7	3.2	1900
11	4.2	4.2	850

Computed exponentially the initial nucleation would run up into the millions. The observations are not, however, in keeping with such a locus, and conform more closely to $1 = d\ (1/d_0 - z\sigma/a)$ or $s = s_0 - \sigma z$ and $ds = a$. For present purposes this is near enough. I shall therefore lay off the aperture, s, as a linear function of the number of the exhaustion, z, for which the observations show per unit of z, in case of sulphur nuclei, $\delta s = .28$, and in case of punk nuclei, $\delta s = .19$. The initial aperture computed herefrom as the mean of six series, in each of which the nucleation was introduced independently, is for sulphur, $s_0 = 3.4$ and for punk, $s_0 = 2.2$. Hence $n_0 = 840{,}000$ in the former case and $n_0 = 230{,}000$ in the latter.

Since the pressure ratio was in each case 1.36, the nuclei in the influx air passing over burning sulphur or glowing punk must have been 3.8 times more numerous. Thus there were nearly 3,000,000 sulphur nuclei and nearly 900,000 punk nuclei per cubic centimeter in the laden air currents entering the condensation chamber.

I shall show in Chapter VI that the equation applicable to the present experiments is

$$n_z = n_Z 10^{(z-Z)\log y} \prod_{Z}^{z-1} (1 - S/s^2),$$

where n_Z is the initial nucleation, y the volume ratio on exhaustion, z the number of the exhaustion, and S an appropriate subsidence constant. The function Π is a product of the terms $(1 - S/s_Z^2)\ (1 - S/s_{Z+1}^2) \ldots (1 - S/s_{z-1}^2)$, so that Z is the number of the exhaustion in which the first corona is seen and $\Pi = 1$. When the particles are as large as is the case for benzol the subsidence function is of prevailing importance and masks the exponential function as all the observations for benzol show. I have carried this method out for water vapor, obtaining consistent results throughout. The present observations for benzol are scarcely systematic enough to make it worth while to compute S, and the experiments should be such in which the diffusion and homogeneity of vapor is insured by continued rotation of the vessel rather than by shaking. But there can be no doubt that, with proper precautions in this respect, the number of nuclei furnished per cubic centimeter by any given nucleator can be determined with benzol vapor as the coronas are all normal, even for large values of δp, with certainty.

4. *Axial colors.*—It is because of the relatively great number of relatively large particles in case of benzol and similar hydrocarbon vapors, that the axial colors are seen, and may be traced into much higher orders than is the case with water vapor. The yellows, browns, etc., of the first order may be easily obtained with the steam jet, though they cannot be produced in the condensation chamber by any means except by pressure differences causing intense spontaneous condensation in moist air. The subsequent violets, blues, etc., however, are here distinctly seen as far as the orange red of the second order, after which the admixture of white light makes recognition of color more and more difficult. With hydrocarbon liquids like gasolene, benzine, etc., the axial colors are seen much farther along the series even through a short column, and they are intense in the drum. The difficulty encountered in observation is due to

the slow diffusion and consequent absence of homogeneous vapor. I hope, however, by *keeping the drum in rotation* around the axis of vision, as already suggested, to counteract this discrepancy, and correspondingly to prolong the series.

5. *Carbon disulphide.*—The vapor of this reagent is another in which coarse normal coronas usually appear. The endeavor to produce the higher coronas with sulphur, punk, or air nuclei fails if the pressure differences are of the same order as those used for water. Particles of the fog are usually about $d = .001$ cm. in diameter for strong nucleation, and the strong coronas produced on shaking showed diameters of the order of $d = .0015$ under the given conditions of exhaustion. Relatively large coronas were obtained with nuclei which apparently rise from this reagent spontaneously. Thus after about 2 hours $d = .002$, after 6 to 15 hours $d = .0012$ cm. was observed. The fact that the coronas increase in size in the lapse of time suggests other explanations than the slow diffusion of vapor or the difficulty in keeping it uniformly saturated when successive exhaustions are made. For in this case coronas would decrease and the size of particles increase, whereas the reverse is observed.

The computation of the number of nuclei per cubic centimeter for carbon disulphide is more precarious in view of the high vapor pressures and the deficiency of data applying throughout the range of temperatures involved. For the case of a pressure decrement of $\delta p = 18$ cm., from 76 cm., and at 20°, the adiabatic fall of temperature would be as far as $-34°$, the rise thereafter due to condensed liquid as far as 5°. This implies 53×10^{-6} grams of moisture per cubic centimeter, whence with the above goniometer the number of nuclei per cubic centimeter would be $n = 34\ (10s)^3 = .10/(10d)^3$.

The coronas obtained by spontaneous nucleation thus correspond to $n = 13{,}000$ after 3 hours and $n = 50{,}000$ after 6 hours or more. Finally, punk nuclei after two or three exhaustions with shaking were still present to the number of $n = 75{,}000$ per cubic centimeter.

CHAPTER V.

THE DIFFUSION OF VAPOR INTO NUCLEATED AIR; A CORRECTION.

1. *Apparatus and manipulation.*—The apparatus with which experiments of the present kind are made is conveniently described by aid of the accompanying diagram. The appurtenances necessary in practice are given in my report on the "Structure of the Nucleus" (*Smithsonian Contributions*, No. 1373, 1903), to which reference has frequently been made. A, Figure 1, is a tall glass vessel about one meter high, either cylindrical or rectangular in section, in the latter case with opposed plate-glass sides. The liquid, L, whose vapors are to be tested, is placed in the bottom. The wide tube, c, is used for sudden exhaustion, while a vacuum gauge, g, registers the pressure differences. The tubes a and b to the top and the bottom of A serve for the admission either of filtered air or of nucleated air. They are used together, one for influx and the other for efflux, in connection with the suction of an aspirator.

When the diffusion of the necessarily heavy vapors from L is to be measured, the air in A is first cleansed of vapor by a current of nucleated air from a to b. Thereafter the stopcocks are closed at a stated time. If now at a subsequent time a sudden exhaustion is made in A through c, for a stated pressure difference, $\delta p'$, shown at g, the progress of the diffusion may be computed from the height of the fog-bank after an allowance is made for the rise due to the exhaustion.

On the other hand, if the aspirating current is of filtered air and moves in the direction from b to a, over the surface of the volatile liquid, the receiver, A, should become uniformly saturated to a high degree throughout. If nuclei are added at a stated time below near the surface of the liquid, the corresponding height of the fog-bank seen on exhaustion at a later time should indicate the rate at which the nuclei diffuse, if they diffuse more slowly than the residual concentration of vapor. This method for nuclei, which I pursued with entire confidence, leads, however, to erroneous results, as the present paper will show; for the diffusion of the nuclei is a much more rapid process than the accompanying complications of vapor diffusion.

2. *Equation.*—To state the case specifically, let p be the vapor pressure relative to the saturation pressure at the temperature ϑ_0, at a time t after diffusion of vapor commences and at a height x above the surface of the liquid in the receiver, A. Then from well-known principles it may be shown that

$$(1) \qquad p = 1 - \frac{2}{\sqrt{\pi}} \int_0^{x/2\sqrt{kt}} \varepsilon^{-q^2}\, dq$$

where k is the coefficient of pressure diffusion.

If the exhaustion at the time, t, is made from air pressure, p_0' to p', corresponding to the temperatures ϑ_0 and ϑ', the relation is approximately $\vartheta'/\vartheta_0 = (p'/p_0')^{(k-1)/k}$ where a correction for precipitated liquid, etc., is needed.

The vapor pressure corresponding to the reduced temperature, ϑ', so obtained after division by the saturation pressure at ϑ_0, is, then, the value of p in equation (1), which therefore, like x and t, is known, so that k may be computed.

3. *Application and data.*—In order to have an example for use in the discussion below, I computed the case for water vapor, which though unsuitable from its lightness for experiment, is convenient for comparison with other vapors, almost all of which are heavier than air. The well-known expansion of (1),

$$p = 1 - \sqrt{\tfrac{2}{\pi}}\{x/2(kt)^{1/2} - x^3/3\times 8(kt)^{3/2} + x^5/3\times 5\times 32(kt)^{5/2} - \cdots\}$$

judiciously manipulated is sufficient for the purpose, though I afterwards availed myself of the tables in Dienger's Method of Least Squares in the absence of larger tables.

The results for water vapor were given in a table, with the time, t, in minutes and the height of the fog-bank, x, in centimeters.

The table also contained a second series of data, for the case in which the diffusion takes place into a vapor $\frac{1}{3}$ saturated, to which reference will be made below. The results of the table may be constructed graphically, showing respectively the advance of diffusion at a given height and at a given time. The

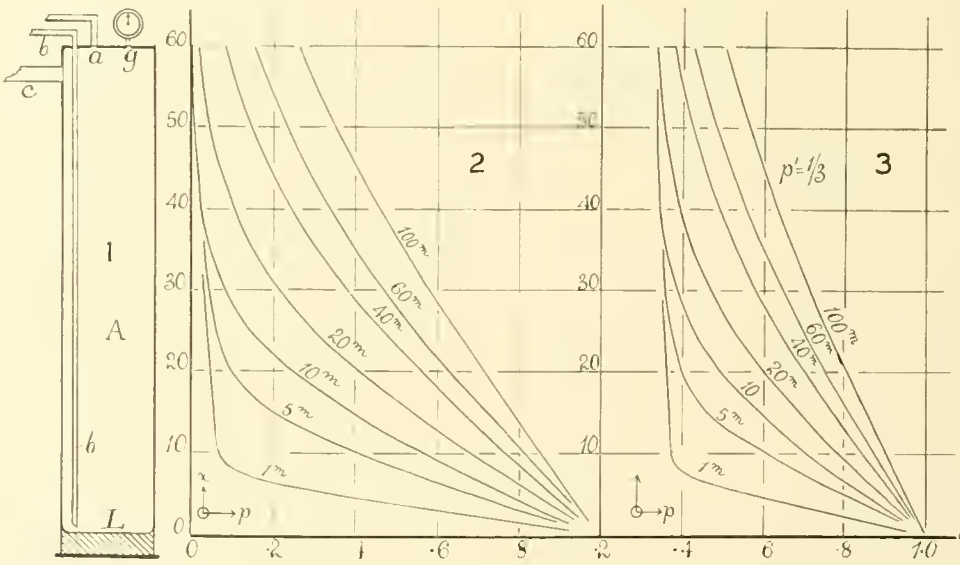


FIGURE 1.—DIFFUSION CHAMBER.

FIGURE 2.—CHART SHOWING THE VAPOR PRESSURES, p, AT DIFFERENT HEIGHTS, x, IN THE LAPSE OF TIME, WHEN WATER VAPOR DIFFUSES INTO AIR.

FIGURE 3.—THE SAME, FOR DIFFUSION INTO AIR ORIGINALLY $\frac{1}{3}$ SATURATED.

latter are exhibited in figure 2, in connection with figure 1. From either set of curves the parabolas which show the rise of a given vapor pressure in the lapse of time may be obtained by graphic interpolation.

If the exhaustion chosen is such as to reduce the vapor pressure to $\frac{1}{3}$ (this corresponds roughly to a pressure difference of $\delta p' = 17$), the intersection of the vertical line of the figure with the successive curves will show the heights of the fog-banks on condensation. Thus after 20, 40, or 60 minutes the fog-banks, having attained heights of, roughly, 22, 33, and 40 centimeters, will be in good position for observation.

For any other vapor than water, the times will increase inversely as the coefficients of diffusion. Thus for benzol the time intervals should be increased about $2\frac{1}{2}$ times.

4. *Conclusions.*—The striking feature of these curves is the extreme slowness of diffusion even for water vapor. At but 20 centimeters above the liquid surface it takes half an hour to reach semi-saturation. The case is accentuated for other liquids where the coefficients are smaller, as, for instance, for the following liquids at about 20°:

Vapor,	H_2O	CH_4O	C_2H_6O	C_3H_8O	C_6H_6	CS_2
$k=$	.23	.16	.12	.07	.09	.1

If, therefore, the fog particles are relatively numerous, large, and subside rapidly, the air will soon become highly de-saturated. In other words, if the air in the receiver *A* is cleaned of nuclei by condensation, there is no vapor available to replace the moisture lost.

In case of water vapor the fog particles are small and subside slowly while the vapor is lighter than air. Hence the latter is liable to be reheated from the rapid radiation of gases assisted by convection, as stated, before much de-saturation takes place, unless the vessel is very long and the sides dry. Precisely the opposite is the case for the hydrocarbon vapors in spite of their volatility, since the fog particles for the same nucleation are larger and fall rapidly, and where the vapors are heavier than air. After successive precipitations at a given pressure difference the vapor may be so far de-saturated that it nearly ceases to condense even if nuclei are present. That it can quite cease to respond is impossible, for some vapor must return to the air after condensation almost instantaneously; but it is not improbable that a vapor exhausted to a slightly higher pressure difference will fail to respond thereafter at the original pressure difference. Thus there is considerable chance for error, and what is taken for the diffusion of nuclei added near the surface of the liquid may actually be the diffusion of the liquid itself. This will even be the case if an aspiration current, as in § 1, falls sufficiently short of saturation, supposing always that the velocity of nuclei is relatively large. True, in the experiments which I made, the two sets of results for nuclei and for vapors differ radically in order of values, in distribution among different vapors, while for carbon disulphide the gradually increasing apertures of the coronas is certain evidence of greater concentration of nuclei. But these and other occurrences may each in their turn be explained away.

5. *Diffusion from greater to less saturation.*—To facilitate the discrimination

in question, the diffusion of vapor into partially saturated vapor may be computed, as has already been done since

$$p = 1 + \sqrt{\tfrac{2}{\pi}}(p_0 - 1)\int_0^{x/2\sqrt{kt}} \varepsilon^{-q^2}dq$$

and the initial saturation is $p_0 = \frac{1}{3}$ at $t = 0$. The results are constructed in figure 3, and from them the parabolas showing the rise of the levels of successively increasing saturation may be derived.

An inspection of figure 3 shows that if the exhaustion were carried somewhat further than corresponds to the lower limit $p = \frac{1}{3}$, the fog-banks would be capped at a definite height, and that the latter would be enormously influenced by slight changes of pressure decrement on exhaustion. Experiment bears this out. Even for fixed pressure differences (δp) the condensation must progress with a sweep from the bottom upward, and if the very small particles last formed evaporate fast enough, an upper demarcation of the fog-bank will again show itself which would easily be mistaken as a true case of the diffusion of nuclei. In this way the diffusion of about semi-saturation ($p = .5$) into benzol vapor initially about $\frac{1}{3}$ saturated would fully account for the apparent diffusion of nuclei into benzol vapor shown in the memoir cited.

6. *Crucial experiment and conclusion.* Special experiments must therefore be made to decide whether, when nuclei are added at the bottom of a homogeneous column of nearly saturated vapor, the observed diffusion is that of nuclei through the vapor, or of a greater concentration of vapor through homogeneous nucleation. For this purpose it is sufficient to add the nuclei in successive experiments at the top and at the bottom of the receiver, A, figure 1. The nuclei in such a case must diffuse alternately downward and upward, while the vapor diffuses upward only. Such experiments since made with care showed that the addition of nuclei above or below the column of vapor is without effect on the observed diffusion. Hence it follows not only that the diffusion of the vapor and not of the nuclei has been observed, but that the nuclei must diffuse much more rapidly than the vapor. Indeed, in the time in which the nuclei travel from top to bottom of the tall vessel nearly 1 meter high, the vapor has scarcely risen, and the fog-bank seen on exhaustion lies close to the surface of the liquid.

An attempt to measure this rapid diffusion of the nucleus in benzol vapor by the present direct method failed, chiefly because all attempts to rigorously saturate the air in the receiver with the heavy vapor in a reasonable time were seriously hampered by convection. The results merely showed that the velocity of the nucleus in benzol vapor must be quite of the same order as in water vapor, but sharp data could not be obtained.

A curious observation, obtained particularly in the case of coronas from alcoholic fog particles, deserves mention. Here the tendency to irregular coronas *decreases* as the number of nuclei becomes smaller. The final coronas are generally regular, though small. It follows from this that the diminished saturation in the upper parts of the vessel, due to the precipitation of fog particles with relatively slow diffusion of vapor, eventually becomes more and more negligible. Hence the small region from which each nucleus draws its liquid charge is apparently limited by the low rate of diffusion relatively to the rate of subsidence of the nucleus. In large coronas, subsidence is slow, and the region from which vapor reaches the nucleus is correspondingly large. In small coronas, subsidence is rapid, and the region from which vapor is received dwindles in local extent.

7. *Nuclei produced by the mixture of coal gas and air.*—Some time ago I noticed that if coal gas is examined by the steam jet or color tube, as described elsewhere,[1] a faint pink flush is seen in the field of the tube. This indicates the presence of nuclei to the extent of many thousands per cubic centimeter in the gas. Inasmuch as such nuclei could not be retained in the gas pipes (they would soon be lost either by subsidence or diffusion), an explanation of the phenomenon was difficult to suggest. Recently I examined the question by the aid of the present method of coronas. Coal gas stored over water and suddenly cooled shows no condensation. It is therefore free from nuclei, as would be anticipated. Filtered air under the same conditions behaves in the same way. If, however, coal gas and filtered air are mixed and then examined, nuclei are abundantly present, to the extent of several thousand per cubic centimeter, showing that chemical reaction (attributable to the presence of sulphide gas as an impurity) has taken place.

If the air is introduced above the lighter coal gas, the nuclei are obtained at once as a result of the mixture, by convection. If the coal gas is introduced above the air, nuclei are not at first in evidence, but they appear later as the result of diffusion at the surface of contact. The case of the steam tube is now obvious, seeing that the gas is here necessarily introduced in contact with air. These nuclei are not ionized, as special experiments with a condenser showed. Very probably the product of the oxidation is sulphuric acid.

[1] See *Experiments with Ionized Air, Smithsonian Contributions to Knowledge*, No. 1309, 1901.

CHAPTER VI.

PERIODIC COLOR DISTRIBUTIONS IN RELATION TO THE CORONAS OF CLOUDY CONDENSATION, WITH A REVISION OF THE CONSTANTS OF CORONAS.

INTRODUCTION.

1. *Purpose and plan.* The growing importance of cosmic dust [1] in relation to geophysic phenomena suggested the need of developing a method by which the atmospheric dust contents could be speedily and systematically determined. An appropriate method for this purpose was tested in a number of my earlier papers [2] which gave promise of being in a measure independent of merely local or accidental dust distributions. It is based on the measurement of the angular apertures of the coronas produced on suddenly cooling moist atmospheric air under definite conditions. Observations of atmospheric nucleation made in this way for about two years show results of considerable interest.

There is some difficulty, however, in reducing these data to absolute values (number of nuclei per cubic centimeter), inasmuch as the coronas obtained with lamp light very frequently pass beyond the ordinary white centered normal type into the more complex forms corresponding to very small particles. I have therefore been obliged to make an extended study of coronas.[3] The method pursued consisted in highly nucleating the air stored within a given receiver over water (with adequate provision for continued saturation), and then withdrawing definite amounts of it by successive partial exhaustions. If the nucleated air is replaced by filtered air free from nuclei, the residual number of nuclei in the receiver must decrease in geometric progression with the number of partial exhaustions. The latter, moreover, produce the sudden cooling by which the coronas are obtained. Let m be the moisture precipitated per cubic centimeter, in any exhaustion, n the number of cloud particles contained, d the diameter of each: then $n = 6m/\pi d^3$. Since for the successive partial exhaustions m is constant, n follows from d, and *vice versa*.

Two methods are available for the absolute measurement of d. One may

[1] The pioneering work of Aitken is well known and cited in my earlier papers.

[2] *Science*, XVI, p. 948, 1902; *Physical Review*, XVI, p. 193, 1902; *ibid.*, XVII, p. 233, 1903.

[3] *Phil. Mag.* (6), IV, p. 24, 1902; *American Journ. of Science* (4), XIII, p. 81, 1902; *ibid.*, XV, p. 335, 1903; *Physical Review*, l. c.; *Smithsonian Contributions to Knowledge*, No 1373, XXIX, pp. 1–176, 1903.

determine the apertures of the coronas (so long as these are normal) by a suitable goniometer, or one may find the rate of subsidence of the cloud particles. Both are approximate and limited in scope, as they fail in the cases of the higher transient coronas. Two methods, furthermore, are available for measuring the nucleation, n, or at least relations of n. Aitken's direct dust counter or a similar apparatus may be applied (work[1] with this end in view is given in Chaps. VII, VIII), or the values of n may be made to decrease geometrically in the way just specified until normal coronas are obtained, for which d follows from aperture. For the last of these methods I have already published data; but in the course of over a year's additional experimentation a number of new developments have shown themselves which it is my purpose here to elucidate. In the first place the method formerly used for determining m gave results much too small. These are corrected in the present paper. In the second place, the coronas were supposed to be observed under adiabatic conditions of temperature; direct experiments in this paper show that the air temperatures during which the coronas are observed are nearly isothermal. Moreover, the new results prove that in addition to the systematic loss of nuclei by exhaustion, as thus fully computed, there is an additional loss which has hitherto escaped me. Each exhaustion, in fact, is accompanied by a definite loss of nuclei for which reasons must be investigated (§ 10).

Finally, I have in this chapter used both electric- and mono-chromatic light as a source, as well as the Welsbach mantel employed for practical purposes. Naturally from the introduction of intense violets the coronas become more complicated, but it is only in this way that their true nature may be detected.

2. *Apparatus.*—The apparatus in which the present experiments were made differs from the earlier forms merely in the employment of plate-glass condensation chambers. A variety of forms were used, some bulky and nearly cubical, like figure 1 (20 cm. deep, 25 cm. high, 35 cm. long), others (figure 2) long and narrow (15 cm. deep, 11 cm. high, 55 cm. long). Practically an apparatus 25 cm. deep, 10 cm. high, or less, and 60 cm. long would be most generally suitable. They were all lined, except on the opposed plate-glass faces, with a double layer of cotton on a copper frame. The chamber is to be mounted on trunnions, E, t, so as to admit of easy rotation around a horizontal axis at right angles to the line of vision. Holes, A, A', must be provided so that the plate-glass may be cleaned within, with a probang. The chamber carries a stopcock, F, leading to a cotton filter, and another, P, leading to the nucleator (preferably phosphorus). The trunnions are wide and hollow, and exhaustion is made through one of them, E, while the other, t, is either closed or may serve for the admission of a thermometer. To produce a definite amount of

[1] Aitken's dust counter may be dispensed with, and the intensity of the nucleator determined by condensation in benzol vapor, in which the coronas are all normal. See *Smithsonian Contributions*, l. c., p. 55 *et seq.*

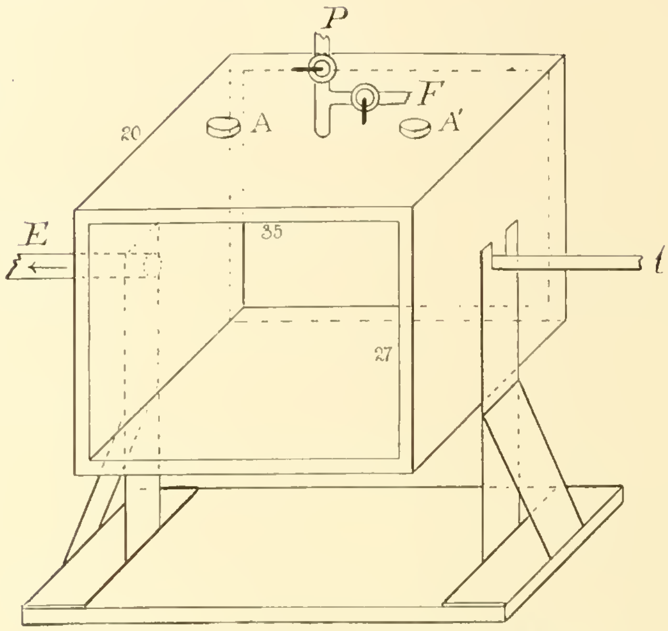


Figure 1.—Cubical Condensation Chamber.

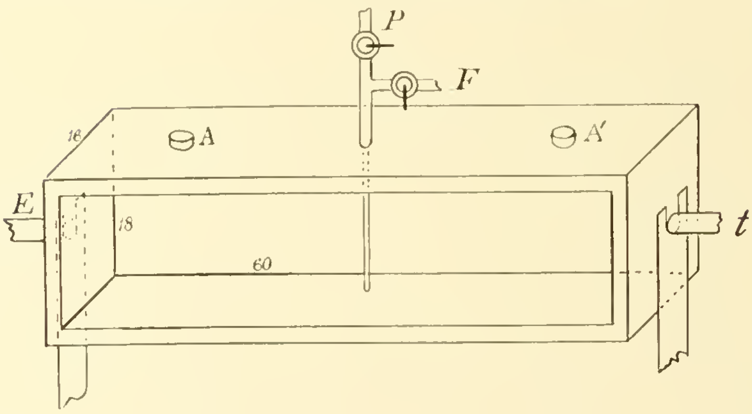


Figure 2.—Long Condensation Chamber.

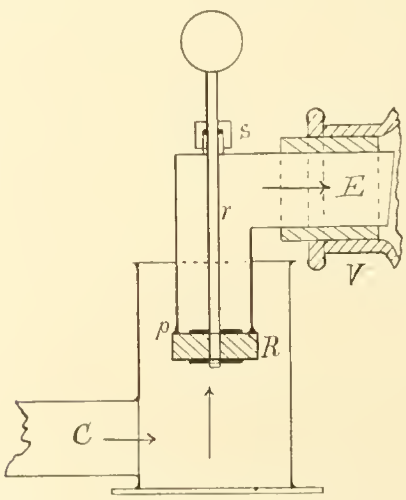


Figure 3.—Valve for Sudden Exhaustion.

exhaustion an external vacuum chamber provided with a mercury gauge and a wide stopcock suffices. A jet pump is suitable for evacuation.

The condensation chamber is placed between the goniometer and the source of light, nearer the former if large coronas are to be obtained. In my experiments the distances were usually 84 and 250 cm., or about as 1/3. The eye at the goniometer is focussed unconsciously on the distant source (334 cm.).

The exhaustions must be made systematically in connection with a seconds clock, to admit of allowance for the time losses. The time during which the fog remains suspended is particularly important, and must be uniform and as short as possible.[1]

3. *Color distributions.*—In classifying the coronas, a statement of the colors of the first two or three annuli, counted from the center, will usually suffice. For the case of the electric light the central patch remains white, or at least opalescent or bluish. With the Welsbach lamp a central disc of vivid green or green-yellow, or even yellow, is frequently observed; but the use of the electric light in parallel series shows this to be due to the absence of strong complimentary blues and violet.

For convenience in specifying color, the following abbreviations will be used throughout: w, white; p, purple; c, crimson; r, orange-red; br, brown; o, orange; y, yellow; g, green; b, blue; v, violet. Mixed colors are written together; thus bg is blue-green, rv red-violet. An accent denotes an approximation to the color; thus b′ is bluish, which has been otherwise indeterminable. A dot or capital denotes a deep or dark color; thus $\dot{\text{b}}$ or B is dark blue. A mere line denotes a color ring too narrow or dark to be recognized. This is the frequent transition from red to green, marked w r g.

Beginning with the most intense nucleation obtainable, *i. e.*, with particles of the least size producible, the following coronas appear in succession, at first filmy and fleeting, but eventually brilliant and dense. The numerals attached to the series are arbitrary.

I. w′ o′

II. w v g′; b′ $\dot{\text{b}}$ r′; w′ g $\dot{\text{v}}$; w y v bg′; w yo v g′; w c yg v′

There is thus an obvious tendency for the colors succeeding white to follow each other in the order of wave length, as the particles continually increase in diameter. All intermediate gradations are represented. The second cycle is nearly complete, the first (?) cannot be obtained except in the opalescent orange tint, unless the steam jet is employed. The second annulus of any corona is apt to vary in width so as to be unequally important.

The next series (III) for successively larger particles is a contraction of the preceding. There is obviously much overlapping. The following types of coronas may be cited. The colors are very brilliant. The second "green"

[1] *Smithsonian Contributions to Knowledge*, l. c.

corona is particularly characteristic, consisting of three broad color bands. The disc is green with the Welsbach lamp.

III. w vp ḃ g′ r′; w g ḃ p; w yo (b) gb r; w ṙ (b) g r′.

The next series (IV) is a variation of w r′ b g r, approaching the steady normal coronas of the next cycle. The colors are very closely packed together, so that it is difficult to produce definite types of them at will. Very small differences of diameter of cloud particle materially change the details of the color scheme. Incidentally, however, the "green" corona, wg′ b p is obtained particularly with the Welsbach lamp; the red of the first ring changes from y′ to br′. w r | g is frequent.

In succeeding coronas the normal type is practically permanent and the observable variation is merely in diameter.

4. *Apertures.*—For the measurement of the relative apertures (s) of the coronas the inner edge of the first ring or the diameter of the white patch is unsuitable, because this demarcation is usually vague. On the other hand, the demarcation between the first and second color rings is usually very sharp and the colors in contrast. Most of the measurements have therefore been made to the outer edge of the first ring. Naturally there will be periodicity from the fluctuation of wave length specified, but this periodicity persists when homogeneous light is employed. Unfortunately, the coronas are usually so faint that the simple means for homogeneous light are not available and electric or sunlight must be employed. For practical purposes, colored annuli are thus inevitable.

The opalescent colors of the series marked II above soon fade. Evaporation takes place while the partially exhausted air is regaining its original temperature. Particles become irregular with no markedly preponderating size. Initial coronas are fleeting, final coronas washed. The evaporation effect is much less evident in Series III and the succeeding series.

DATA OBTAINED WITH THE WELSBACH BURNER.

5. *Explanation of tables.*—To correlate the present with my earlier investigations I will give a series of results found by using a small circular part of the Welsbach mantel as a source of light. Coronas in this case are more easily identified because of the simplified color scheme, to the practical advantages of which I have already referred.

In table 1, z denotes the number of the partial exhaustions each of volume ratio, y, and made in succession, t, the current time in minutes (the interval being about 3 minutes to allow for adjustments and for diffusion), s the chord of the angular radius, φ, at radius R, so that $s/R = 2 \sin\varphi$. The eye and source of light were at distances 85 and 250 cm. from the intervening condensation chamber, and the former was focussed for long distances. The pressure and temperature of the atmosphere were P and θ, and the fixed pressure decrement on exhaustion uniformly $\delta p = 17$ cm., nearly, so that the precipitate per cub. cm. is $m = 4.7 \times 10^{-6}$. Measurements were made to the outer edge of the first ring. In the column marked "coronas," the color of the annuli is specified from within outward, using the abbreviations stated above. The nucleation is marked n' if computed from the aperture s standardized with lycopodium, n'' if computed from s standardized by subsidence measurements, N if computed relatively as a geometric progression, n when the latter is reduced as shown below, and the absolute values corrected for time and exhaustion losses, etc. The initial nucleation is shown under n_0, and corresponds to $z = 4$. The other coefficients, β, referring to time losses, α referring to exhaustion losses, S referring to subsidence losses, will be presently explained. Though n is measured for the partially exhausted receiver, a final correction $(1/y)$ need not be added, for the influx of filtered air leaves the nucleation undisturbed. The ratio $n'/N = 275\ s^3/10^{z \log y}$ constructed in the charts shows the wide departure from the constancy which would be anticipated. Diameters of the fog particles are given under d, the accents referring to the method of computation. All data will be fully discussed below.

6. *Charts.*—The charts show the relations of important quantities in the tables. Thus $r = n'/N$ may be laid off in relation to the number of the exhaustion, z, as in figure 5; but, generally, the nucleations, n, and finally the diameters, d, of the fog particles, are given in terms of the apertures, s, where the angular radius $\varphi = s/60$.

7. *Tables.*—The data investigated for the Welsbach burner follow.

TABLE 1.—CONSTANTS OF CORONAS. WELSBACH LAMP. CONDENSATION CHAMBER, 20 cm. BROAD, 25 cm. HIGH, 35 cm. LONG; DISTANCES OF EYE AND SOURCE OF LIGHT FROM CHAMBER, 85 cm. and 250 cm., RESPECTIVELY; $\theta = 22°$; BAROM., 75.34 cm.; $\delta p = 16.9$; $y = .77$; $\alpha = .064$; $\beta = 0$; $S = 2.65$; $a'' = .0029$ (SUBSIDENCE); $a' = .0032$ (LYCOPODIUM); $n_0 = 209000$; PHOSPHORUS NUCLEI. $d'' = .0029/s$; $m = 4.7 \times 10^{-6}$. MEASUREMENT OF s TO OUTER EDGE OF FIRST RING.

z	t	s	Corona.	$n' = 275\ s^3$.	$n'' = 370\ s^3$.	$NII\ (1 - \frac{S}{s^2})$	n_0	n	$d = .021\ n^{-1/3}$.
0	min.	cm.		$\times 10^{-3}$	$\times 10^{-3}$	(2.84)	$\times 10^{-3}$	600000	cm.
1	17	—		—	—	(2.19)		460000	.000270
2	20	—	b′ r′	—	—	(1.69)		355000	290
3	23	—	g′	—	—	(1.30)		273000	320
4	27	10.3	y o b	300	403	1.000		210000	350
5	30	8.3	w c g	157	212	.751		158000	385
6	34	6.8	w p b· g′	86.3	116	.557		117000	425
7	37	6.0	g b· p	59.4	70.9	.403		84600	475
8	41	5.8	w r g	53.6	72.2	.289		60700	530
9	44	4.6	w br b· p	26.7	36.0	.204		42800	595
10	48	4.2	w r g	20.4	27.4	.137	200	28800	680
11	51	3.7	corona	13.9	18.8	.090	208	19000	780
12	54	3.2	"	9.0	12.1	.055	221	11500	920
13	57	2.6	"	4.8	6.5	.032	205	6700	.001110
14	60	2.0	"	2.2	3.0	.015	199	3100	1430
15	63	1.3	"	.6	.8	.004	220	800	2250

TABLE 1.—SECOND SERIES. $n_0 = 190000$; $a = .061$.

z	t	s	Corona.	$n' = 275\, s^3$.	$n'' = 370\, s^3$.	$NH\ (1 - \frac{S}{s^2})$	n_0	n	$d = .021\ n^{-1/3}$
0	—	—	—	—		(2.84)		540000	.000256
1	4	—	—	—		(2.19)		416000	278
2	7	—	b′ b˙	—		(1.69)		321000	304
3	10	—	g′	—		(1.30)		247000	331
4	13	10.6	y o b	327	440	1.000		190000	362
5	16	8.3	w c g[1]	157	212	.751		143000	398
6	19	6.0	g b˙ r	59.4	79.9	.557		106000	440
7	22	5.6	yg o bg	48.4	65.1	.398		75600	492
8	25	5.3	w c g	41.0	55.1	.280		53200	555
9	28	4.4	g′ | b˙ | p	24.2	32.6	.196		37200	623
10	31	4.0	w c g	17.6	23.7	.130	182	24700	715
11	34	3.6	w br b˙g′r	12.8	17.3	.083	207	15800	830
12	37	2.9	corona	6.7	9.0	.050	181	9500	980
13	40	2.4	"	3.8	5.1	.027	189	5100	.001200
14	43	1.9	"	1.9	2.5	.011	230	2100	1630
15	46	1.5	"	.9	1.3	.002	—	400	2850
16	49	1.0	"	.3	.4	—	—	0	—

[1] Gap in coronal sequences probably due to accidental delay. Similar difficulties at end of series. Timed fog intervals desirable.

METHOD OF REDUCTION.

8. *Constants of the geometric progression.*—To determine whether the factor of the geometric progression of successive nucleations, z, was to be computed isothermally or adiabatically, a series of direct temperature measurements was deemed necessary. These were made by aid of a thermocouple of extremely thin wires (.007 cm. in diameter), of copper and german silver. The junction within the receiver was not soldered, but the flexible copper wire looped once around the other. In this way the variation of the instantaneous air temperature in the receiver could be closely followed. It was necessary to use a sensitive astatic galvanometer, and the measurements are thus subject to the fluctuations of the earth field. As it is the immediate purpose of these data to determine about how soon the isothermal conditions are re-established by radiation from without, the irregularities are of little consequence.

Table 2 contains three series of results, the upper end of each row corresponding to the period of exhaustion, the lower to that of (slow) refilling. Readings were taken in intervals of half a minute. The table shows that after the lapse of one minute following the sudden exhaustion the temperature has been regained to within a degree. As the coronas can hardly be observed and measured within this time, the exhaustion ratio may be computed isothermally. I have therefore computed the density ratio of nucleation $\rho/\rho' = n/n'$, before and after exhaustion, as follows.

Since $p = R\rho\vartheta$ in the usual notation of Boyle's law, and $p = P - p'$ where P

is the reduced reading of the mercury gauge and p' the vapor pressure of water vapor,

$$\rho/\rho' = (P-p)\ (1-\delta\vartheta/\vartheta)/(P'-p').$$

The correction $\delta\vartheta/\vartheta$, being by the table $.7/293 = .0024$ or about $\frac{1}{4}$ per cent., may be neglected. Hence $y = \rho'/\rho = 1 - \delta p/(P-p')$, where δp is the pressure difference selected. Thus in table 1, N, not corrected for time losses, etc., would be

$$N = y^z = 10^{z \log y} \text{ where } y = .77 \text{ and } N = 10^{-.1135z}.$$

In this way the auxiliary ratios n'/N in the tables were constructed. This is the first departure from the method of my earlier work (*Smithsonian Contributions*, No. 1373).

TABLE 2.—AIR TEMPERATURE [1] IN CONDENSATION CHAMBER DURING AND AFTER SUDDEN EXHAUSTION AND DURING INFLUX.

Time after exhaustion.	1st Series °C.	2d Series °C.	3d Series °C.
0^m [2]	$-10.7°$	$-10.7°$	$-10.8°$
.5	$-$ .7	$-$ .8	$-$ 1.1
1.0	$-$ .7	$-$ .8	$-$ .7
1.5	$-$ .7	$-$ .7	$-$ .7
2.0	$-$ .7	$-$ .4	$-$ .5
2.5	$+1.4$ [3]	$-$ .3	$-$ .5
3.0	1.4	$+1.2$ [3]	$-$ .4
3.5	.7	2.0	$+$ 1.8 [3]
4.0	.4	1.1	1.1
4.5	—	.5	1.1
5.0		.3	.4
5.5			.3
6.0			.1

[1] Irregular march after exhaustion due to unsteady earth field.
[2] Throw on sudden exhaustion.
[3] March on filling slowly with filtered air.

9. *Time losses.*—Nuclei apparently decay spontaneously in the lapse of time, t, and a correction is to be added to N. Since this loss is relatively small in view of the short time intervals occurring above, $n = n_1 10^{\beta(t-t_1)}$ may be assumed for convenience. Hence if n be the nucleation due to a given corona seen at low pressure or the identical nucleation at atmospheric pressure after filtered air has been added, the next corona after z exhaustions and t minutes will correspond to $n_1 = n\ 10^{z \log y + \beta(t-t_1)}$ whence

$$\beta = (1/(t-t_1))\log(n_1/n\ y^z).$$

Thus it is merely necessary to know the relative values of n or the nucleation ratios, and these may be obtained by any method of smoothing, by plotting n' or N in terms of s.

In table 1, N has been found for each aperture, s, and β computed as stated. The values of β so found are of the mean order of .002. They apparently decrease toward the end of each series as the number of nuclei grows smaller; but this conclusion is not vouched for, as it will presently be shown that a specific loss of nuclei accompanies each exhaustion. In other words, $n = Nr_0\ (1-\alpha z)$, where r_0 is a constant, or the numbers diminish faster than is attributable to time loss alone. The effect will be particularly marked for the smaller initial time intervals of the original nucleations.

Accordingly I have made another computation, writing approximately

$$n/n' = (N/N')(1+\alpha\,(z'-z))$$

and finding β from this by the equation already given. These values of β are inserted in the last column of the table. They are irregular in distribution and of the mean value $\beta = .0016$.

The chief result of this paragraph is the relatively small value of the coefficient of time loss of nuclei. Its effect on the results may therefore be neglected (tested), particularly as the effect $10^{.0016z} = 1.004$ for $z=1$ is in part compensated by the temperature factor $\delta\vartheta/\vartheta = .0024$ of the preceding paragraph. Direct experiments below (§§ 27, 28), where identical results are obtained for different time intervals (2 min. and 4 min.), vouch for this conclusion. Measurements of coronal aperture of the present kind, hampered as they are by the difficulties of observation, of reduction, of subsidence, etc., cannot offer more than an estimate of the conditions sought.

10. *Exhaustion losses.*—I shall next consider the independent destruction of nuclei which accompanies each exhaustion, and for which it is difficult at the outset to assign a reason. It will be shown that it is due to the subsidence of fog particles. This loss did not appear in my original investigations, probably because the spherical receiver used was not lined with wet cloth.

From what has preceded, the relative number of nuclei after z exhaustions is $10^{z \log y}$, whereas in the region of normal coronas the absolute number is certainly very nearly $n' = Cs^3$, where C is a constant. This will be independently verified presently by special experiments. Hence the ratio $r = Cs^3/10^{z \log y}$ should be constant, whereas experiment and the charts, figure 5, show (roughly) that $r = r_0\ (1-\alpha z)$, α being the coefficient of exhaustion loss and $r_0 = Cs_0{}^3$ the arbitrary initial ratio for $z=0$, preceding the first corona observed. Thus

$$\alpha z = (1-(s/s_0)^3/10^{z \log y}).$$

If $r=0$ for $z=z'$, $1/z'=\alpha$, so that α appears as the reciprocal of the abscissa underlying the positive ordinates in the first quadrant, and may be taken at once from the graphs. These values are given at the head of each table.

TABLE 3.—CONSTANTS OF CORONAS, COMPUTED BY SUPPOSING α = CONST. DISTANCES OF EYE AND SOURCE 85 AND 250 cm. FROM RECEIVER, RESPECTIVELY. $\theta = 22°$; P = 75.34 cm.; $\delta p = .16.9$; $y = .759$; $n = n_0 10^{-.12z}(1 - \alpha z)$; $\alpha = .062$; $\beta = .002$. MEASURED TO OUTER RED, INNER BLUE OR GREEN. $n_0 = 750000$; $m = 4.7 \times 10^{-6}$; $a = .0032$; $6m/\pi d^3 = 275 s^3$. *P* IONIZER.

FIRST SERIES.

z	t	s	Corona.	$n' = 275s^3$	$N(1-\alpha z)$	n_0	$n = n_0 10^{-.12z} \times (1-\alpha z)$	$r = n'/N \times 10^3$
	min.	cm.						
1	17		nucleation.					—
2	20		b′ r′		.504		460000	—
3	23		− g′		.355		323000	—
4	27	10.3	y o b	300000	.249		227000	300
5	30	8.3	w rc g	157000	.173		157000	204
6	34	6.8	w p′ B g′	86300	.120		109000	146
7	37	6.0	g′ B p	59400	.082		74700	130
8	41	5.8	w r g	53600	.055		50400	152
9	44	4.6	w br B|p	26700	.037		33500	99
10	48	4.2	w or g	20400	.024	8500000	21800	98
11	51	3.7	corona	13900	.015	9100000	13900	87
12	54	3.2	"	9000	.009	9700000	8500	74.5
13	57	2.6	"	4800	.005	9000000	4900	51.0
14	60	2.0	"	2200	.003	8000000	2500	30.0
15	63	1.3	"	600	.001	5400000	1000	10.7
						mean, 9100000		

SECOND SERIES.

z	t	s	Corona.	$n' = 275s^3$	$N(1-\alpha z)$	n_0	$n = n_0 10^{-.12z} \times (1-\alpha z)$	$r = n'/N \times 10^3$
	min.	cm.						
1	4		nucleation.					
2	7		b′ B		.504		378000	—
3	10		g′		.355		266000	—
4	13	10.6	y o b	327000	.249		186000	327
5	16	8.3	w c g	157000	.173		130000	204
6	19	6.0	g B r	59400	.120		90000	100
7	22	5.6	yg o bg	48400	.082		61600	106
8	25	5.3	w c g	41000	.055		41500	117
9	28	4.4	g′ B|p	24200	.037		27600	89.5
10	31	4.0	w c g	17600	.024	740000	18000	85.0
11	34	3.6	w br B g′r	12800	.015	840000	11500	79.5
12	37	2.9	corona	6700	.009	720000	8400	55.5
13	40	2.4	"	3800	.005	710000	4000	40.0
14	43	1.9	"	1900	.003	680000	2100	26.0
15	46	1.5	"	930	.001	830000	825	16.6
16	49	1.0	"	270	.000	—	—	6.3

NOTE:—In $N = 10^{-.12z}$ the constant is corrected for time loss. This practice was later abandoned. (§ 9). The constant in n' is obtained from earlier measurements with lycopodium. The auxiliary column n'/N has been used in the charts.

The occurrence of different slopes in the curves is an obvious result of the unavoidable differences of initial nucleation. The effect is a shifting of the z values. Thus in two series for the same corona similarly observed, but with independent initial nucleations, $r=r_0(1-\alpha z)=r'_0(1-\alpha' z')$, where $z'=z-z'_0$; whence $\alpha'=\alpha/(1-\alpha z'_0)$, the constant z'_0 being the index of the difference of initial nucleations.

A computation on the assumption of constancy of α was made for comparison, and is given in the preceding table, 3, corresponding to table 1 above, and with the same notation.

11. *Exhaustion loss attributable to subsidence.*—The misleading feature of α is its apparent constancy for a given receiver and a given scheme of observations. It will now be shown that this result is a mere approximation and that the phenomenon may be fully explained in terms of subsidence. In this case, $10^4 R=9\sqrt{v}$, where R is the radius of the water particle and v its rate of subsidence. Since $2R=d=.0032/s$, approximately, $v=(1.78)^2/s^2$, or if v' refers to minutes, $v'=190/s^2$.

The relative loss, l, per minute, is for a vessel of height h and nucleation n, $l=v/h=190/hs^2$. If, as in the above condensation chamber, the height is $h=26.5$ cm., $l=7.2/s^2$, or, in tabular form,

$s=$	1	2	3	4	5	cm.
$l=$	7.2	1.8	.80	.45	.36	

numbers which are astonishingly large, but must be near the truth.

Let the time consumed in observation be 1/2 min. and 1/4 min., respectively; then the ratio r in table 1 may be corrected in the region of normal coronas as follows:

TABLE 4.—CORRECTION OF $r=275s^3/10^{z\log y}$ IN TABLE 3, SHOWING THE EFFECT OF SUBSIDENCE.

z	$r\times10^{-3}$	s	$\frac{l}{2}$	$r\times10^{-3}$ corrected.	$\frac{l}{4}$	$r\times10^{-3}$ corrected.	Mean $r\times10^{-3}$ corrected.
10	98.0	4.2	.21	98.0	.10	98.0	98.0
11	87.0	3.7	.26	108.0	.13	97.0	103.0
12	74.5	3.2	.35	118.5	.18	95.5	107.0
13	51.0	2.6	.51	121.0	.28	85.4	103.0
14	30.0	2.0	.90	126.0	.45	79.0	103.0
15	10.7	1.3	—	130.0	.75	73.0	102.0

The first of these values of r is under-corrected, while the second r is over-corrected. The mean of these corresponding to a time of observation of $\frac{3}{8}$ minute is constant. Now as the time during which the fog is left undispelled after exhaustion for measurement is actually of this order, there can be no question but that the error is due to subsidence. The equation should therefore read:

$$n=Cs^3=n_0 10^{z\log y}(1-S/s^2_0)(1-S/s^2_1). \quad . \quad .$$

as will be more fully explained below. Here S is an appropriate subsidence constant depending on the mean time of observation or on the time within which nuclei are suspended in the fog particles. Conformably with this view α or S depends essentially on the height of the vessel in which the condensation is produced, being larger, *cœt. par.*, in shallow vessels, seeing that v/h is larger. (§ 25).

12. *The optic constant.*—The proportionality of diameter with the inverse aperture may be assumed for normal coronas. The occurrence of periodicity in the higher coronas, even if merely a question of color were involved, would modify these simple conditions for these cases. It is well known that for a single particle, the masterly work of Lommel[1] has given a complete treatment of the diffractions in terms of Bessel functions.

In meteorological work for a particle of diameter d and for uniformly normal coronas, the equation $\sin\varphi = 1.22\lambda/d$ is usually assumed, if the angular radius of the corona is φ and the wave length in question λ. Since in my goniometer $2\sin\varphi = s/R$, where $R = 30$ cm., $ds = a = 73.2\lambda$. Hence, for the successive spectrum colors, the following values obtain for the constant a:

color,	c	r	o	y	g	b	v
$a=$	.0051	.0046	.0044	.0042	.0039	.0034	.0029

In view of the theoretical uncertainty of these values in the case of the distribution of particles met with in the above experiments, I have usually relied on the results of direct comparisons with the corona of lycopodium spores where $d_0 = .0032$ cm. Placed in the position of the near plate of the coronal chamber, the corresponding aperture for lycopodium spores was $s_0 = 1.05$ cm., at the far plate, $s_0 = 1.03$. Hence $a = d_0 s_0 = .0034$ for measurements to the *outer* edge of the first ring. This corresponds to the preceding value for blue, though these apertures were measured through ruby glass. In the above tables, where merely relative results were in question, $a = .0032$, a datum of earlier measurements, was inserted. Reduction was deemed needless. For the case of measurements to the *inner* edge of the first ring or to the edge of the white disc, $s_0 = .7$ to $.8$, the demarcation being more vague. Assuming the latter, $a = .0026$ for such measurements. Still more troublesome is the measurement of a when the condensation chamber is remote (250 cm.) from the goniometer and near (85 cm.) the source. The datum was $a = .00125$ from $s_0 = .39$.

13. *The optic constant. Diameters from subsidence.*—This is an independent method of standardizing s. In my earlier work the condensation chamber was not cloth-lined, and the subsidence data quite untrustworthy, showing rapid retardation of abnormally high initial values due to evaporation. In the present cloth-lined receiver kept wet on all sides, subsidence data are reasonably satisfactory. The coronas, however, change character during subsidence, and in case of the initial opalescent coronas (Series II above) all coronas vanish into a mere fog before subsidence is even appreciable. Finally, the upper plane

[1] Lommel, *Abhandl. der kön. Bayerischen Akad. der Wissensch.*, xv, 1886.

boundary of the fog, which at the outset appears as a sharp horizontal line about 50 cm. long, even after 1 or 2 min. becomes more and more vague. Subsidence is here accelerated. Hence it is chiefly for the normal coronas that subsidence data are available, and, fortunately, it is precisely here that they are wanted. In other cases the occurrence of periodicity and the rapid change of coronas makes the interpretation tedious and difficult.

The following table contains the results for subsidence. Stokes's well-known formula reduces to $R=9\times10^{-4}\sqrt{v}$ where R is the radius of the fog particle sought. Temperature is denoted by θ and current time by t, depth of the fog line by x, and rate of subsidence by v. The diameter computed from aperture is inserted for comparison. $2Rs=a$ is the new optical constant sought. The braces denote the observations of x taken to compute v whenever the corona changes character.

It appears from the earlier parts of this table that although the coronas may shrink and change appearance, this is not in the same measure the case with the rate of subsidence. In the latter parts of a given series of observations, therefore, the diameters from aperture are always in excess of those from subsidence. With the growth of droplets, the two phenomena refer to different particles, and hence only the original observations, *i. e.*, those within the first minute, are of any value.

TABLE 5.—SUBSIDENCE OF FOG PARTICLES. PHOSPHORUS NUCLEI. VISCOSITY OF AIR, $\eta=.00019$.

FIRST SERIES.

θ	t	Corona.	s	x	v	$2R\times10^4$	$10_4\times\frac{.0032}{s}$	$2R.s=a$
°C.	h. m.		cm.	cm.	cm./sec.	cm.	cm.	
15°	11 1	w r g	9.1	0	.030	3.1	3.5	.0028
	2			2				
	3	shrunken		4.5				
	4	and foggy		8.5				
				0				
	6	g b p	6.4	3	.047	4.0	5.0	.0026
	7							
	8	w br b | p			.042			
	9	w o b	5.8	5.5	.047	4.0	5.5	(.0023)
				8.5				
	13	corona		0	.092	5.4	6.3	.0027
	14		5.1	5.5				
	15			11.0				
	16			15.0				
				0				
	21	corona	2.8		2.4	8.8	10.0	.0025
	21.5			7				
	22			17				

Second Series.

θ	t	Corona.	s	x	v	$2R \times 10^4$	$10^4 d$	$2R.s = a$
	h. m.							
15°	11 43	g′ b′ p	6.8	0	.025	2.9	3–4.7	.0020
	44	w′ r′		1.5				
	48	w o g	9.7	0	.025	2.9	3.3	.0032
	49	foggy		1.5				
	50	w′ r′	5.5	4.0	.042	3.8	5.8	(.0021)
	54	w p b	6.8	0	.042	3.8	4.8	.0025
	55		(6.7)	2.5	(.046)			
	56	w′ o′ (foggy)	6.5	5.5	.050			
	57	w′ o′	5.2	9.0	.058	4.1	6.2	(.0021)
	12 1	w o g	6.0	0	.071	4.9	5.5	.0029
	2			4.0				
	3		5.5	8.5				
	4			13.0	.075	4.9	6.0	(.0027)
	13	w cḃ g′r′	4.2	0	.158	7.2	7.8	.0030
	13.5		4.1	4				
	14	w′ o′	4.0	9.5				
	14.5	w′ o′	3.9	14.	.167	7.4	8.0	(.0030)

Third Series—Air Nuclei.

θ	t	Corona.	s	x	v	$2R \times 10^4$	$d \times 10^4$	$2R.s = a$
	h. m.							
15°	12 20	w b p	4.5	0	.11	5.9	7.3	.0026
	20.5		4.4	3.5				
	21		4.4	6.5				
	21.5	w br ḃ | p	4.3	10.0	.11	5.9	7.3	(.0025)
	22		4.3	?12.5				
	26	corona	3.2	0	.22	8.5	10.0	.0028
	26.5			6				
	27			15				

FOURTH SERIES.

θ	t	Corona.	s	x	v	$2R \times 10^4$	$d \times 10^4$	$2R.s = a$
15°	0	w br ḃg′ p	4.7	0	.105	5.8	6.8	.0027
	.5			3				
	1.			6				
	1.5			9				
	2.0			12				
	0	corona	3.4	0	.225	8.5	9.3	.0029
	.5			5				
	1.0			13				
	1.0			19				
	0	w br ḃ g′ r	5.1	0	.083	5.2	6.3	.0026
	.5			2.5				
	1.0			5.2				
	2.5							
	2.0			10.0				
	0	w o g	5.9	0	.078	5.0	5.4	.0029
	.5			2				
	1.0			4				
	1.5			7				
	2.0			9				
	0	w o ḃ g	4.6	0	.133	6.6	7.0	.0030
	.5			3.5				
	1.0			7.5				
	1.5			12.0				
	0	corona	3.1	0	.300	9.9	10.3	.0031
	.5			6				
	1.0			17				
	1.5			25				
	0	w c g	5.5	0	.083	5.2	5.7	.0029
	.5			2.5				
	1.0			5.0				
	1.5			7.5				
	0	w r | g	4.5	0	.153	7.0	7.1	.0031
	.5			3.7				
	1.0			9.0				
	1.5			1.3				
	0	corona	3.0	0	.300	9.9	10.5	.0030
	.5			6				
	1.0			17				
	1.5			26 +				

It is nevertheless interesting to note that the values of a obtained are of a reasonable order of values even for the higher coronas, in which periodicity supervenes. The corresponding graph (not shown) brings this out clearly. If the values of a which correspond to normal coronas be selected, the following summary is obtained:

TABLE 6.—VALUES OF a FROM APERTURE AND SUBSIDENCE.

Series.	Corona.	s	a	Mean.
1	normal	5.1	.0027	
1	"	2.8	25	
2	"	4.2	30	
3	w b p	4.5	26	
3	normal	3.2	28	
4	"	4.7	27	
4	"	3.4	29	
4	"	5.1	26	
4	w o b g	4.6	30	.00291
4	normal	3.1	31	
4	w r g	4.5	31	
4	normal	3.0	30	
mean			.00283	

The mean of all the series is $a = .00283$; the mean of the fourth series, which is more uniform, $a = .00291$. The latter datum will be taken in the following computations.

14. *Summary of optic constants.*—The following series of values of $a = ds$ has been obtained when the measurements of aperture are made to the outer edge of the first ring.

Optically (blue),	$a = .00344$
From lycopodium ($d_{ii} = .0032$),	.00336
From subsidence,	.00291

The latter datum is decidedly the smaller, corresponding closely to optical puce-violet (.00293). If, in place of the above expression, the elementary optical equation $2 \sin \varphi = s/R = \lambda/d$ or $a = 30\lambda$ had been taken instead of $a = 73.2\lambda$, even the extreme red would show but $a'' = .0023$.

The datum for subsidence being simplest in character is apparently the most trustworthy. Since $n = (6m/\pi a^3)\ s^3$, if the method of Wilson and Thomson[1] be used for the computation of m the following values in grams per cubic centimeter are applicable at the temperatures stated, for the pressure difference $\delta p = 17$ cm.:

$\theta =$	10°	20°	30°
$m =$	3.7×10^{-6}	4.6×10^{-6}	5.7×10^{-6}

[1] *Cf.* J. J. Thomson, *Phil. Mag.* (5), XLVI, p. 538, 1898.

For the pressure difference $\delta p=22$ cm. which will occur below,

$m=$ 4.2×10^{-6} 5.5×10^{-6} 6.7×10^{-6}

For $\delta p=8.5$ cm.

$m=$ 2.1×10^{-6} 2.6×10^{-6} 2.8×10^{-6}

The effect of temperature on latent heat is not considered, since the data are not fully known. Its effect may be 1 to 2 per cent. More important is the value to be taken for the heat ratio $\gamma=1.41$.

15. *Resulting equations applied.*—From what has been stated, it follows that the first quantity to be found is the initial nucleation, n_0, *i. e.*, the nucleation which obtains when $z=Z$. This depends on incidental conditions, such as the intensity of the ionizer, the first corona seen (Z), etc., and is therefore quite arbitrary. In table 1, for instance, $n_4=n_0$. Hence

$$n_z=n_0 10^{(z-4)\log y}(1-S/s_4^2)\ (1-S/s_5^2)\ (1-S/s_6^2)\ldots(1-S/s_{(z-1)}^2),$$

which will be abbreviated

$$n_z=n_0 10^{(z-4)\log y}\prod_4^{z-1}(1-S/s^2).$$

This equation affords in the first place a means of computing S. For in the region of normal coronas n is given by the apertures of the coronas. If, for brevity, $r_z=n_z/10^{z\log y}$,

$$r_{z+1}/r_{z-1}=(1-S/s_{z-1}^2)(1-S/s_z^2),$$

from which S is determinable in terms of pairs of values of r and s; or S may be even more simply found from two successive normal coronas. The following table shows the values found for the two series in table 1.

TABLE 7.—VALUES OF S FROM $r_{z+1}/r_{z-1}=1-S\ (1/s_{z-1}^2+1/s_z^2)+S^2/s_{z-1}^2 s_z^2$.

	$r\times 10^{-3}$	$1/s^2$	$1/s_{z-1}^2 s_z^2$	S	Mean S.
SERIES 1. TABLE 1.	100 132	.130	.0041	1.97	
	68.4 117	.171	71	2.70	2.66
	40.5 100	.245	144	2.83	
	144 68.4	.397	367	2.44	
SERIES 2. TABLE 1.	39.4 114	.139	.0048	2.73	2.63
	53.7 107	.196	92	2.88	
	397 74.6	.294	.0208	2.27	
	31.3 53.7	.453	486	1.84	
	26.3 34.9	.722	.1230	2.02	

As both series were made in the same way, the mean value $S=2.65$ will be inserted. With this value of S the data of the column $NII\,(1-S/s^2)$ may be computed throughout. Then in the region of normal coronas the fundamental constant of the reduction follows as

$$n_0 = 370 s^3 / NII\,(1-S/s^2).$$

With this constant, the true value of the nucleation (number of particles per cub. cm.) is computed for all coronas as

$$n = n_0 NII\,(1-S/s^2).$$

All these data are found in table 1. It should be noticed that the coefficient 370 is obtained from subsidence.

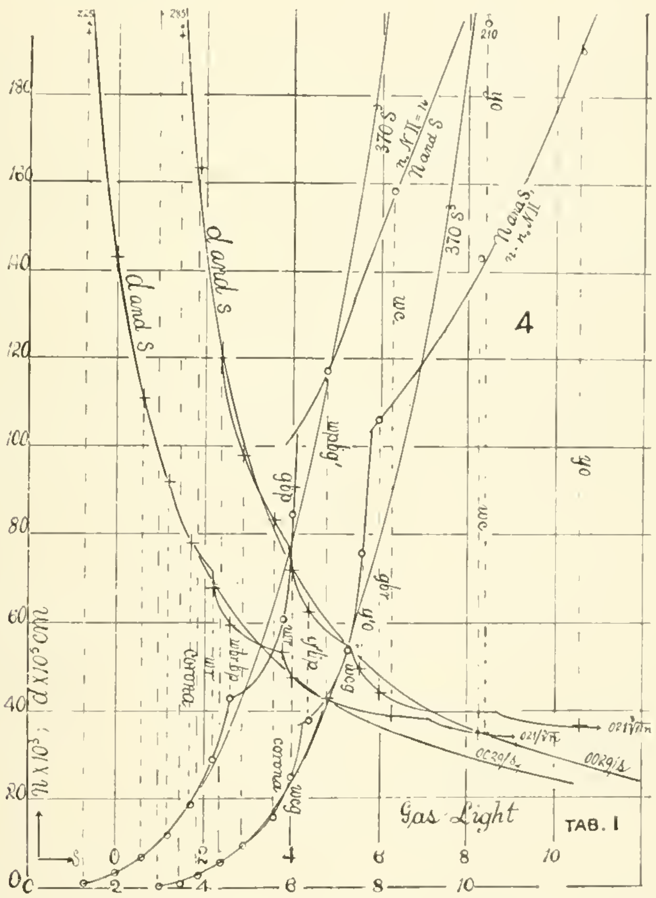


FIGURE 4.—CHART FOR TABLE 1, SHOWING THE RELATION OF NUCLEATION (n) AND OF DIAMETER (d) OF FOG PARTICLE IN TERMS OF THE APERTURES (s) OF THE CORONAS.

16. *Remarks on the tables and graphs.*—The graphs, figure 4, for tables 1 and 3, show four independent series of observations of diameter, d, and nucleation, n (particles per cub. cm.), in terms of the relative aperture, $s=60\ \sin\varphi$, where

φ is the angular radius. The partial exhaustion is to 17 cm. and the standardization is by subsidence (§ 14). If standardized by diffraction, the n-data would be about .6 smaller, or the upper "green" corona, for instance, showing $n=98{,}000$, would then show $n=60{,}000$ nuclei. The d effect is much smaller, being .2 larger.

Towards the end of any series the numbers diminish more slowly than the formula requires, but this is naturally the result of the evaporation seen, for instance, in the shrinkage of the coronas. On the other hand, when subsidence is exceptionally rapid, the time during which subsidence takes place, and which can in no case be sharply given (it was not directly timed), is seriously large. On the whole, the agreement is better than was anticipated, and certainly trustworthy. The results coincide in a general way, moreover, with the data found by assuming a constant as was done in §§ 5, 9, and the latter equations may be regarded as approximations by expansion of those in this section.

The graphs, n in terms of s, give evidence in the first series of three cycles, the lower two being merged. In the second series there are apparently four cycles, the two lower being distinct. The horizontal position of the cusps is as closely in accord as the measurements justify. The vertical position suffers from the shift and difficulty surrounding the absolute evaluation of n. Throughout their extent, however, the fundamental similarity of the graphs is unmistakable, as will be further shown in the corresponding curves for ruby light below.

Since $n'=6m/\pi d^3=(6m/\pi a^3)\, s^3=23\,(s/10^4\lambda)^3$, approximately, the fluctuation of n with λ is obvious; but the feature of the phenomenon is none the less *the occurrence of cyclic variations in the color of the innermost ring.* The correction implied in the last equation would be more than sufficient. The violet coronas are to be depressed as regards n and the red coronas raised in their n values, showing that in the former the measurement referred to red surpassing the last violet, and in the latter to violet beyond the red. It is expedient to state these data in relation to the diameters of the fog particles under observation.

17. *Diameter of fog particles.* Having determined the true values of n, the diameters of fog particles may be computed for each aperture, since

$$d=\sqrt[3]{6m/\pi n}=.021n^{-1/3}.$$

The results are given in the tables and are plotted in the corresponding graphs. Each of these (d as a function of s) shows the three cycles already determined, and the cusps lie at $d=.0007$ to .0008 cm. and $d=.0005$ to .00055 cm., or that the intermediate and particularly luminous cycle covers a range corresponding to about ten times the wave lengths (.00004 to .00008 cm.) of the visible spectrum. But two of the cusps are unmistakably marked, while in other respects the graphs retain the hyperbolic contour, $ds=$const.

Since $n^{-1/3}$ is the cubical volume which contains one fog particle, $d/n^{-1/3}$

is the ratio of the diameter of particles to the distance between particles, constant throughout. The distance between centers is thus about 48 times the diameter of particles for the temperature and pressure conditions prevailing during the exhaustions.

One may note that the diameters found are independent of m; for in the above notation let z and D refer to the normal corona virtually used for standardization. Then, as the series stands,

$$n_z = n_0 10^{(z-4)\log y} \prod_{4}^{z-1}(1 - S/s^2),$$

or after reduction, since the same equation also holds for Z,

$$1/d^3 = (s_0/a)^3 10^{(z-Z)\log y} \prod_{Z-1}^{z-1}(1 - S/s^2)$$

where s_0 is the aperture of the normal corona numbered Z. Thus d depends on a, y, and S, and does not therefore differ much from my earlier values except in so far as a and y were differently determined and S not observed.

Finally, since $nd^3 = 6m/\pi = \text{const.}$, the relation of n and d are reciprocal, and maxima in n thus correspond to minima in d. If d is determined too large, n will be too small. The curves bear this out. The periods indicated by the cusps in the d curves are more appropriately referred to below. They may be placed as follows: in the first curve they lie at $d = .00069$, .00053, .00039; in the second at about $d = .00079$, .00055, .00040 cm. In conformity with the work below their mean position may be rated at $d = .00072$, .00054, .00036, or in the ratio of 4, 3, and 2. In other words, they are, roughly, multiples of the cycle datum .00018 cm., and throughout large as compared with wave length.

MONO-CHROMATIC LIGHT.

18. *Tables.*—The coronas are too faint for effective observation with mono-chromatic light obtained from simple sources like the salt flame. I therefore used the electric arc as a point source and obtained sufficient limitation for the present with a double thickness of ruby glass. This arrangement has an ulterior advantage as it is thus possible to observe the colors of the annuli as well as their red diameter on interposing the colored glass. This greatly facilitates the reductions. The observations made with the large cubical condensation chamber are given in the following table arranged on the same plan as the preceding. The constant a'' is as before definitely determined from subsidence, while a' refers to preliminary standardization with lycopodium. The time loss β is neglected. The subsidence loss has been separately computed and differs slightly from the above, showing more expeditious work.

TABLE 8.—CONSTANTS OF CORONAS. ELECTRIC AND RUBY LIGHT. CONDENSATION CHAMBER AS IN TABLE 1. DISTANCES AS IN TABLE 1. $\theta = 15.5°$; BAROM., $= 75.8$ cm.; $\delta p = 16.9$ cm.; $y = .77$; $\alpha = .0632$; $\beta = 0$; $S = 2.5$; $m = 4.2 \times 10^{-6}$ GRAMS; $a'' = .0029$; $a' = .0032$; $n_0 = 188000$; PHOSPHORUS NUCLEI; $d'' = .0029/s$. MEASUREMENT TO OUTER EDGE OF FIRST RING. $2 \sin \varphi = s/R$.

FIRST SERIES.

z	t	s	Corona.	$n' = 250s^3 \times 10^{-3}$	$n'' = 335s^3 \times 10^{-3}$	$N\Pi(1 - \frac{S}{s^2})$	$n_0 \times 10^{-3}$	n	$d = .020n^{-1/3}$
0	min.	cm.							
1	41	—	—	—		(2.2)		412000	.000269
2	44	—	v′ g′ r′	—		(1.7)		318000	293
3	48	—	w′ y g′ v′	—		(1.3)		244000	320
4	51	9.0	w o p g	182	244	1.000		188000	349
5	55	8.3	w′ c y g	145	195	.746		140000	385
6	58	6.5	w g b p	70.2	94.1	.554		104000	426
7	62	5.7	w y g b	47.5	63.6	.402		75600	473
8	65	5.4	w r g	39.2	52.6	.286		53800	531
9	68	4.7	w g b p	26.0	34.8	.201		37800	595
10	71	4.2	w r b g	19.2	25.7	.137	188	25800	676
11	74	3.7	w y b g	12.7	17.0	.091	186	17200	775
12	78	3.1	w o b g	7.8	10.5	.056	186	10500	913
13	81	2.7	corona	4.9	6.6	.033	200	6200	.001090
14	84	2.1	"	1.9	3.1	.017	188	3100	1370
15	87	?1.4	"	.7	1.0	.006	180	1000	1960

SECOND SERIES.—$n^0 = 200000$; $\alpha = .0610$.

1	—	—	—	—	—	2.2		440000	.000264
2	54	—	w′ g′	—	—	1.7		340000	287
3	57	—	w g v	—	—	1.3		260000	314
4	61	9.5	w y g	214	287	1.000		200000	342
5	64	8.8	w c g	170	228	.770		149000	378
6	68	7.1	w g b r	89.5	120	.593		112000	415
7	71	6.0	w g v r	54.0	72.3	.457		81200	462
8	74	5.7	w o g	46.2	62.0	.352		58600	514
9	77	5.2	w g b r	35.2	47.2	.271		41600	576
10	80	4.3	w o b g	19.9	26.6	.208	183	29000	652
11	83	4.1	w o b g′r′	17.2	23.1	.161	238	?19400	744
12	87	3.3	corona	9.4	12.6	.121	203	12400	866
13	90	2.8	"	5.5	7.4	.095	197	7500	.001020
14	93	2.2	"	2.6	3.5	.073	181	3900	1270
15	96	1.6	"	1.1	1.5	.056	210	1400	1770
16	99	1.2	"	.4	.6	.043	135	800	2130

19. *Graphs for nucleation.*—The results for mono-chromatic light are constructed in the chart, figure 6, and show the three prominent cycles with suggestions of others crowded into the region of normal coronas; but the latter are uncertain. The two curves are more closely in agreement both in their horizontal and vertical dimensions than was the case above. All four curves agree, however, in their essential points, as closely as may be expected. The

region of lower cusps is between $n=35{,}000$ and 45,000, and of the upper cusps between $n=95{,}000$ and 105,000, or at $s=4.5$ and $s=6.0$ in the two cases. These cusps mark the region of "green" coronas. The angular radius is $\varphi=4°\ 18'$ and $\varphi=5°\ 44'$, respectively. Other remarks already made apply here.

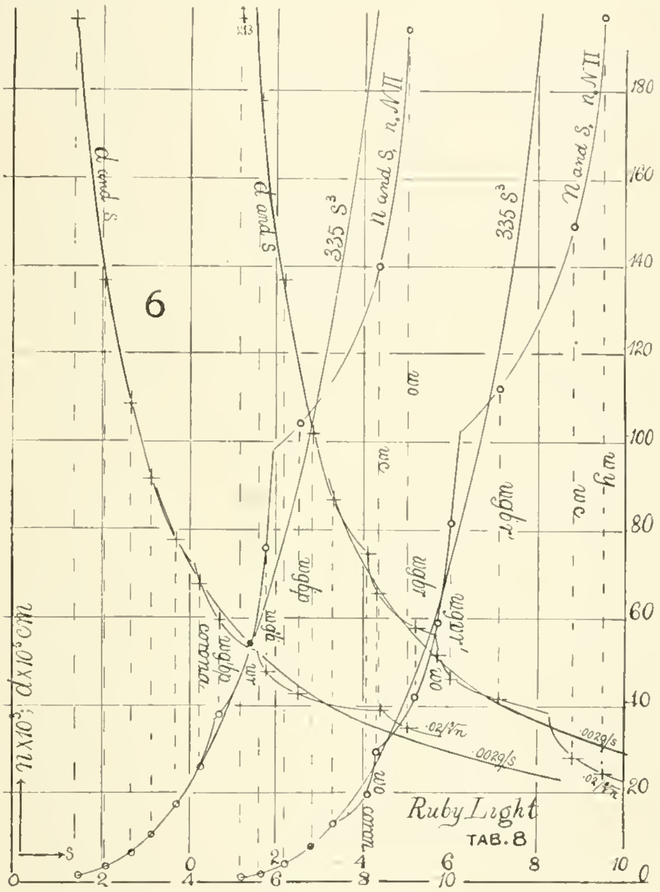


FIGURE 6.—CHART FOR TABLE 8, SHOWING THE RELATION OF NUCLEATION (n) AND OF DIAMETER OF FOG PARTICLE (d) IN TERMS OF THE APERTURES (s) OF THE CORONAS.

20. *Graphs for diameter.*—There is a slightly different constant involved here, as the temperature is lower. Since $\theta=15.5°$,

$$d=\sqrt[3]{6m/\pi n}=.020n^{-1/3}.$$

Hence the edge of the cube containing one fog particle is just 50 times the diameter of the particle for the uniform conditions of condensation selected.

The curves for d'' (smooth hyperbola since $d''s=\text{const.}$) and d are drawn in relation to s as usual, and the latter give evidence of three or more cusps with intervening minima. These in their maximum and minimum relations are reciprocal with the corresponding curves for n. Both curves agree with each other and with the preceding set for d.

Horizontal positions are naturally better than vertical positions because of the shifting attending the standardization of n and d. If the horizontal position of the cusps be taken from the figure as $s=2.7$, 4.2, 5.6, 8.3 in curve 1 on the left, and $s=2.8$, 4.1, 5.6, 8.3 in curve 2 on the right, the mean ratios are 2, 3, 4, 6, so that $s=1.4$ or $\varphi=1^\circ\ 18'$ repeats itself. Since $d=.0029/s$ nearly, the d ratios should be as 1/2, 1/3, 1/4, 1/6. The figure shows roughly in curve 1 $10^6d=1100$, 710, 540, 400, and in curve 2, $10^6d=1050$, 740, 550, 350, the means of which values are in the ratio of 6, 4, 3, 2, as nearly as can be expected, the data being multiples of .00018 cm., here as above. The presence of a period between 4 and 6 is not in evidence.

MISCELLANEOUS EXPERIMENTS WITH THE DEEP VESSEL.

21. *Measurement to the edge of the white disc.*—Before citing data obtained from measurements of the aperture of the disc, it is desirable to reduce the preceding data, s_o (aperture to the outside edge of the first ring) to s_i (aperture to the inside edge of the first ring) by direct experiments. This is done in the next table (9). The relation within the normal region is practically linear and $s_i/s_o=.76$.

Careful inspection of the coronas seen with electric light shows that even when normal the edge of the white disc shades off through y, o, br, etc. There is no real demarcation of the white disc, but the r' edge is rather the beginning of a diffraction cycle in which (counting from the outside inward) r, o, y, merging into white, appear, and when the higher coronas are reached the missing g, b, v become evident in their turn.

TABLE 9.—OUTSIDE AND INSIDE DIAMETERS OF THE RED RING. DISC, w w′ y′ br′ vp′ b g y′ r; EDGE, a w y HAZE. MEAN RATIO, $s_i/s_o=.77$.

Corona.	s_i	s_o	s_i/s_o	Corona.	s_i	s_o	s_i/s_o
w y br b g y′ r	2.1	3.0 2.9	.72	w|r b g	3.1	4.2 4.2	.74
Do.	2.4	3.1 3.0	.78	w o b g	2.8	3.5	.81
				Do.	2.2	2.9 3.0	.75
w y o b|r	4.0	5.1 4.8	.80	Do.	2.7	3.4 3.4	.79
w g b|p change to w y g	3.6	4.6 4.5	.78	N. corona	2.2	2.9	.76
w o b g′	4.0	4.9 4.6	.83	"	1.8	2.5	.74
w y′ r|g	3.2	4.3 4.4	.73	"	1.3	1.9	.69

Measurements of s_o before and after s_i.

Table 9 shows that if $ds_o=.00291$ (subsidence), then

$$a_1=ds_i=.00291\times.77=.00223 \text{ and } n=(6m/\pi a_1^3)\ (10s)^3=810s^3.$$

Direct measurements of the a_1 by comparison with lycopodium gave $s_1 = .78$ and .84 for the near and far faces of the chamber whence $a_1 = .0026$ (diffraction) and $n = 515s^3$. This is in the usual way smaller, and n/s^3 larger than the subsidence datum ($a_1 = .00223$), but the latter will be taken here as above. Both values are compared in the tables, the ratio being $.64 = n'/n''$.

22. *Apertures of the discs of the coronas.*—Table 10 contains two independent series of results arranged as in the preceding tables. The source of light is the Welsbach mantel. The data are further shown in figure 7.

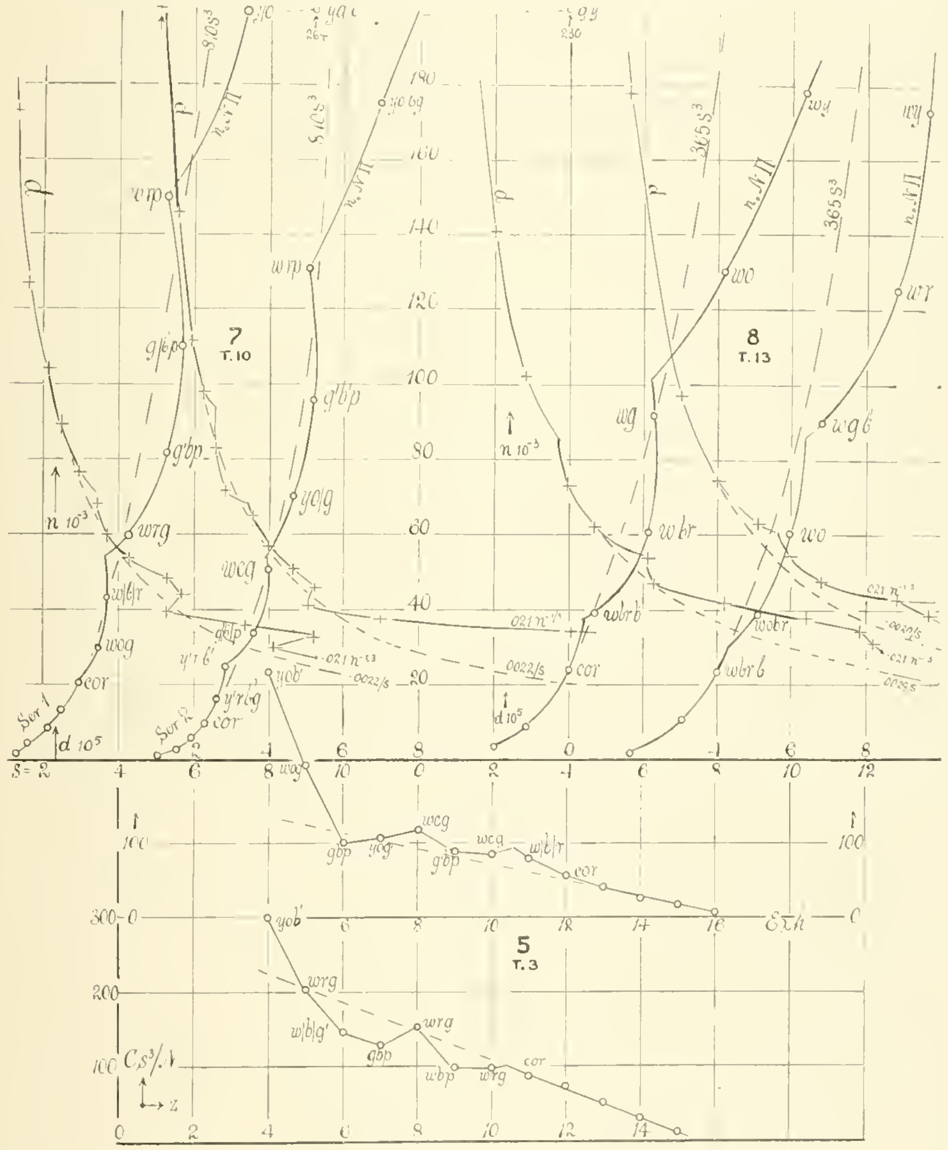


FIGURE 5.—CHART SHOWING THE RELATION OF RELATIVE NUCLEATION (r) TO THE NUMBER (z) OR ORDER OF THE EXHAUSTION FOR TABLE 3.

FIGURE 7.—CHART SHOWING THE RELATION OF THE ACTUAL NUCLEATION (n) TO THE NUMBER (z), OR ORDER OF THE EXHAUSTION, FOR TABLE 10. ALSO THE DIAMETER d (IN 10^{-5} CM.) OF THE FOG PARTICLES IN TERMS OF z.

FIGURE 8.—DO. FOR TABLE 13.

TABLE 10. CONSTANTS OF CORONAS. CHAMBER AND DISTANCES AS ABOVE. $\theta=21°$; BAROM., 75.3 cm.; $\delta p=16.9$ cm.; $y=.77$; $\alpha=.062$; $\beta=0$; $S=1.3$; $a'=.0026$; $a''=.00223$; $m=4.7\times10^{-6}$ grams; $n_0=200000$; s MEASURED TO INNER EDGE OF FIRST RING (APERTURE OF DISC); PHOSPHORUS NUCLEI; WELSBACH LAMP.

z	t	Corona.	s	$n'=515s^3$	$n''=810s^3$	$NII(1-\frac{S}{s^2})$	$n=n_0 NII$	$d=.021\ n^{-1/3}$
	min.		cm.	$\times 10^3$	$\times 10^3$			cm.
1	9	—	—			2.8	560000	.000255
2	12	g′ r′	—		·	2.2	440000	277
3	15	g′ b′	—			1.7	340000	300
4	18	yg o	9.2	401	631	1.32	264000	328
5	22	y o bg	7.4	208	328	1.000	200000	360
6	25	w c|g	5.3	76.7	121	.751	150000	395
7	29	g′ b p	5.7	95.3	149	.552	110000	440
8	32	g′ b p	5.3	76.7	121	.408	81600	485
9	36	w r g	4.3	41.0	64.4	.299	59800	537
10	39	w br b|r	3.7	26.1	41.0	.215	43000	600
11	43	w o|g	3.4	21.2	33.3	.149	29800	680
12	46	N. corona	2.9	13.2	20.8	.103	20600	765
13	50	"	2.5	8.0	12.6	.066	13100	890
14	53	"	2.1	5.1	8.0	.041	8200	.001040
15	57	"	1.6	2.3	3.6	.022	4500	1270
16	60	"	1.3	1.1	1.8	.009	1800	1730

SECOND SERIES.—$\alpha=.061$; $n_0=175000$.

z	t	Corona.	s	$n'=515s^3$	$n''=810s^3$	$NII(1-\frac{S}{s^2})$	$n=n_0 NII$	$d=.021\ n^{-1/3}$
				$\times 10^3$	$\times 10^3$			
1		—	—	—	—	2.2	385000	.000288
2	56	—	—	—	—	1.7	300000	314
3	59	gy	11.0			1.3	230000	343
4	63	y o bg	6.9	173	272	1.000	175000	375
5	66	w c b g′	5.0	66.4	104	.749	131000	414
6	69	g′ b p	5.2	72.6	114	.548	96000	460
7	73	y o|g	4.6	51.5	81.4	.401	70200	510
8	76	w c|g	4.0	33.0	51.8	.290	50800	570
9	79	g|b p	3.6	24.0	37.7	.206	34000	650
10	82	y′ c b g	2.8	11.9	18.7	.142	24800	720
11	86	y′ rb g	2.6	9.1	14.2	.0924	16200	830
12	89	corona	2.3	6.3	9.9	561	9800	980
13	93	"	1.9	3.8	6.0	333	5800	.001170
14	96	"	1.5	1.9	3.0	169	2960	1460
15	101	"	1.0	.6	1.0	.0060	1050	2060

The subsidence constant must be smaller in this case, since $S_{z+1}=s_z^2(1-s_{z+1}^3/ys_z^3)$, and it is clear that S and s^2 must change in the same ratio nearly. It was shown that $s_1=.77s_c$, or $s_1^2=.59s_c^2$, and hence $S_1=2.6\times.59=1.56$. An actual computation gave $S_1=1.3$, the difference being easily referable to incidental discrepancies.

23. *Remarks on the table and graphs.*—The green corona now shows the nucleations $(110{,}000+82{,}000)/2$ and independently 96,000, in the two series, agreeing reasonably well with the above 85,000, 106,000, 104,000, 96,000, the

standardization being throughout by subsidence. This agreement is further substantiated below. The difference of values here is largely an actual difference in the positions of the coronas.

The curve $r=515s^3/10^{7\log y}$ if constructed in full shows the eventual linear march already instanced. As above $\alpha=.062$ nearly.

The curves of nucleation, n, in terms of the relative aperture, s, indicate the occurrence of four cycles, though the lower is uncertain. Both curves run in parallel as nearly as the observations allow, and they show actual cases of overlapping or reëntrance.

This reëntrance is particularly evident in the d curves in which four distinct branches overlapping at their edges may be made out. The positions of the cusps, as indicated by the green coronas, may be placed at $10^6 d=450$, 650, 950, cm. or about in the ratio of 3, 4, and 6 times .00015 cm. The corresponding number found above was larger than this in the ratio of 18/15, while the ratio of the red and blue wave lengths involved would be 1.4.

24. *Condensation chamber remote from the eye.* The distances are inverted in the following experiments, being 250 cm. from the eye to the condensation chamber and 85 cm. from this to the source. All coronas therefore are relatively small and the measurement of s by the same method much more difficult, particularly in relation to standardization. Measurement of s was naturally made to the outside of the first ring. Results with lycopodium seen through ruby glass and a source of electric light gave ($d_0=.0032$), $s_0=.344$ cm. Hence $a=d_0 s_0=.0011$ and $n=6750s^3$. If the value of a be reduced to the conditions holding for subsidence, $a''=.0011\ (291/336)=.953\times10^{-3}$, whence $n=10{,}400s^3$. Table 11 computed with this value follows. Unfortunately, three important data were lost, and the series are deficient in this respect.

TABLE 11.—CONSTANTS OF CORONAS. CHAMBER AS ABOVE. DISTANCES FROM EYE AND SOURCE, 250 cm. AND 85 cm. RESPECTIVELY. $\theta=21°$; BAROM., 75.3 cm.; $\delta p=16.9$ cm.; $y=.77$; $\beta=0$; $S=.36$; $n_0=260000$; $a'=.0011$; $a''=.00095$; $m=4.7\times10^{-6}$ grams; s MEASURED TO OUTER EDGE OF FIRST RING; PHOSPHORUS NUCLEI; WELSBACH MANTEL.

z	t	Corona.	s	$n'=6750s^3$	$n''=10400s^3$	$NII\ (1-\frac{S}{s^2})$	$n=n_0\ NII$	$d=.021\ n^{-1/3}$
	min.		cm.	$\times 10^3$	$\times 10^3$			cm.
1	21	—	—	—	—	2.2	570000	.000254
2	24	w′ r′	3.6	315	486	1.7	440000	276
3	28	g′ b′ p′	3.7	356	549	1.3	338000	302
4	32	y o bg	3.4	265	409	1.000	260000	330
5	36	w c g v	3.0	182	281	.747	194000	363
6	40	w p b g′r	2.2	76.9	119	.556	144000	400
7	44	g b p	2.3	82.3	127	.404	105000	446
8	48	w r g	2.0	58.0	89.4	.290	75400	496
9	52	w br b g′r	1.7	33.1	51.0	.205	53300	560
10	56	w y o b g′	—	—	—	.141	36700	633
11	60	coronas	1.2	13.2	20.4	.094	24400	724
12	64	"	1.1	10.3	15.9	.059	15300	850
13	69	"	1.0	6.7	10.4	.035	9100	.001000

SECOND SERIES.—$n = 280000$.

				$\times 10^3$	$\times 10^3$			
1	24	—	—	—	—	2.2	620000	.000246
2	27	w′ r′	4.0	432	666	1.7	480000	268
3	30	g′ b′ p′	3.6	328	505	1.3	360000	295
4	34	y o bg	—			1.000	280000	321
5	39	w r g	3.1	201	310	.747	209000	354
6	43	w c g′	2.4	99.2	153	.556	156000	390
7	47	g b p	2.2	71.5	111	.404	113000	435
8	51	w ro g	2.2	71.5	111	.290	81200	485
9	55	w c|g|r′	1.8	42.5	65.5	.205	57400	544
10	59	g′|b|p		—		.141	39500	616
11	62	w c|g r′	1.3	16.7	25.7	.094	26300	705
12	65	w o b g	1.1	10.3	15.9	.059	16500	824
13	70	corona	1.0	6.7	10.4	.035	9800	980

The n values in their relation to s work out similarly to the above data. The two cusps are in their usual location. The green coronas correspond to $n = 105,000$ and 113,000 nuclei, respectively, somewhat larger than the above order of values, but not more so than the difficulties of standardization would lead one to anticipate.

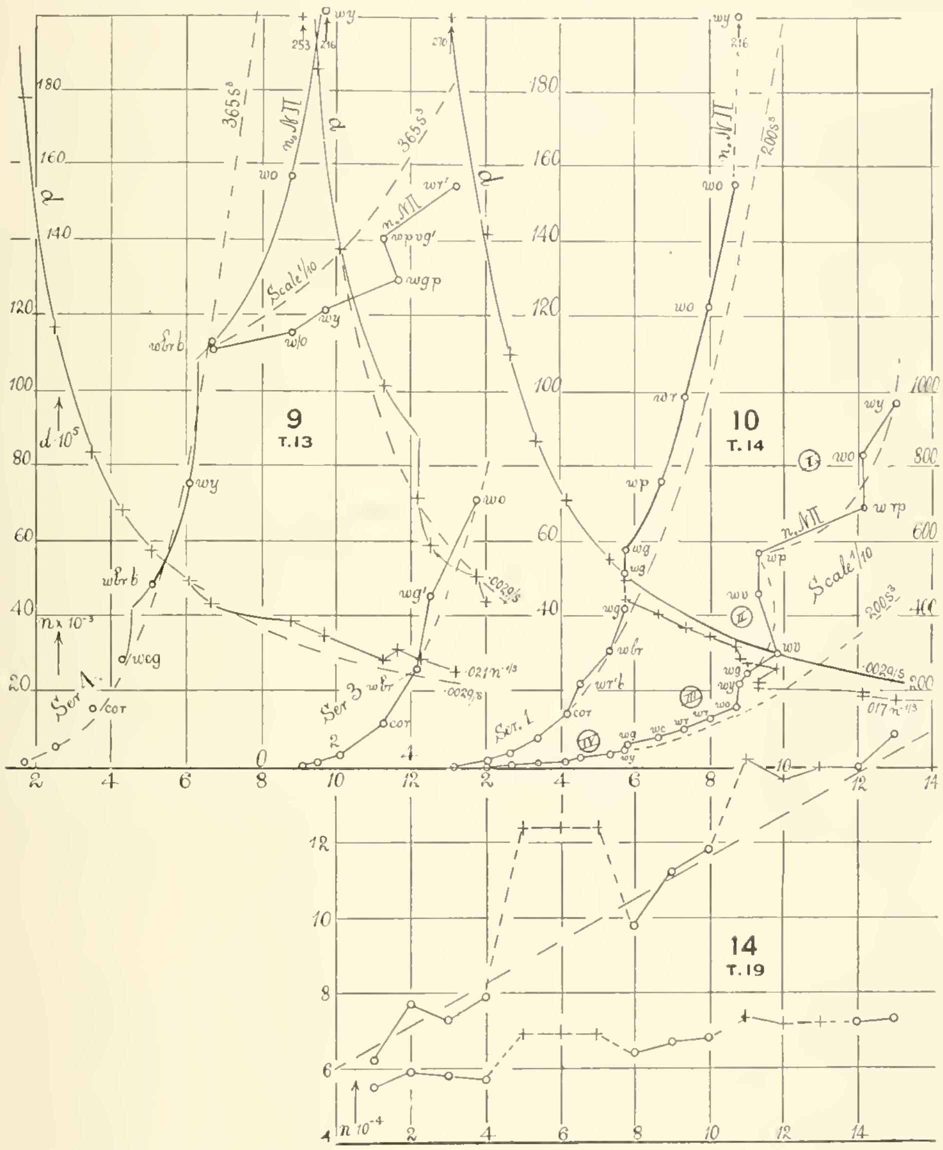
The d values are difficult to interpret, as the curve is fairly uniform but for the break introduced in the w g b p region. Both curves are in close agreement, and under the circumstances it is impossible to locate the cusps and their relations.

LONG AND SHALLOW CONDENSATION CHAMBERS.

25. *Apparatus.*—The purpose of the present section is primarily to give greater scope for the observation of the higher coronas, *i. e.*, those of large aperture. Incidentally it affords a means of testing the validity of the correction for subsidence, S.

To obviate fragility of apparatus and inconvenience in the exhaustions, the volume of the long vessel is suitably decreased by lessening the height. This does not interfere with the work, since only a diametral section of the color rings is needed while the apparatus becomes more manageable.

The vessel is shown in the diagram, figure 2 (above, p. 58), and is (in the clear) 55 cm. long, 11 cm. high, and 16 cm. deep in the line of vision. Less height and even greater depth and length would have been preferable, but in such a case the correction for subsidence becomes unwieldy. As usual, there is a central brace and a lining of wet cloth, and the front and rear faces are of plate-glass $\frac{1}{4}$ inch thick. Exhaustion is effected through the wide hollow trunnion, E, the other being closed and holding a thermometer, or other accessories. F is the filter and P the nucleator, both attached with a cock. Rubber corks, A, A', close the wide holes necessary for cleaning. The external vacuum chamber was such that the pressure differences were reduced about one half on suddenly opening the wide cock into the condensation chamber. There was no leakage, and the easy means of wetting the whole inside by revolution of the apparatus around the trunnions was a great convenience. But in spite of this, color distortion of the coronas was an almost invariable occurrence, particularly when the interval between observations was short. Since in comparison with the case of the taller



Figures 9, 10.—Charts for Tables 13, 14, showing the Nucleation (n) and the Diameters (d) of Fog Particles for Different Apertures (s) of the Coronas.

Figure 14.—Chart showing the Effect of Different Valves with Nucleations Increasing in the Lapse of Time, for Table 19.

vessel above, which showed no appreciable distortion, vapor diffusion is here much enhanced, the discrepancy must be referred to the diffusion of nuclei. This would have to take place unassisted by the convection of vapor.

26. *Reduction of data.*—For the pressure difference $\delta p = 17$ cm. and at 20.7°,

$m = 4.7 \times 10^{-6}$ grams, and therefore, as above, $n = 365s^3$. The constancy of S is less evident than above, being in the respective series

I	II	III	IV	Mean
$S = 6.8$	4.8	6.5	5.5	5.8
7.3	8.5	6.5	6.4	
	4.2	2.1	3.9	
		1.1		

the variability being, however, largely due to the accidental delays inevitably encountered in observing. Nevertheless some other cause is at work simultaneously toward the end of the series. Here the nuclei are not removed apparently.

The mean value $S = 5.8$ will be accepted for the body of the observations, but toward the end of the series the special values computed for S will be inserted as well as the alternative mean values. The ratio of heights of the condensation chambers here and above is $11/26 = .42$, while the inverse ratio of the subsidence constants is $2.6/5.8 = .45$, showing close consistency for experiments of the present kind. Table 13 for $\delta p = 17$ cm. will now be intelligible.

Since $n = 6m/\pi d^3$, it follows that $d = .021n^{-1/3}$, so that the last column follows from the preceding.

The charts, figures 8 and 9, corresponding to these tables, show the cycles already mapped out above, but less distinctly, from the difficulty of maintaining homogeneous nucleation. Naturally, the large coronas, being vague in outline, are difficult to measure, and the middle cycle thus comes out clearest.

TABLE 13.—CONSTANTS OF CORONAS. CONDENSATION CHAMBER 55 cm. LONG, 11 cm. HIGH, 16 cm. DEEP; DISTANCES FROM EYE AND SOURCE, 85 cm. AND 250 cm. RESPECTIVELY; $\theta = 21°$; BAROM., 75.6 cm.; $\delta p = 16.9$ cm.; $y = .77$; $\beta = 0$; $S = 5.8$; $a' = .0032$; $a'' = .0029$; $m = 4.7 \times 10^{-6}$; $n_0 = 173000$; s MEASURED TO OUTER EDGE OF FIRST RING; PHOSPHORUS NUCLEI; ELECTRIC ARC.

FIRST SERIES.—RUBY LIGHT.

z	t	Corona.	s	$n' = 275s^3$	$n'' = 365s^3$	$NII\ (1 - \frac{S}{s^2})$	$n = n_0 NII$	$d = .021\ n^{-1/3}$
	min.		cm.	$\times 10^3$	$\times 10^3$			
1	2	w r g	—	—	—	1.7	294000	.000315
2	4	v g r	—	—	—	1.3	225000	345
3	6	w y p g	9.7	251	333	1.000	173000	378
4	8	w ro g	8.8	191	253	.722	125000	420
5[1]	10	w g b r'	6.8	86.3	115	.515	89100	470
6	12	w o g b p	5.9	58.0	77.0	.347	60000	540
7	14	w o b r g	5.1	36.6	48.5	.222	38400	625
8	16	corona	4.0	17.6	23.4	.133	23000	740
9	18	"	3.0	7.8	10.4	.059	10200[2]	970
10	20	"	1.6	1.2	1.6	.010	1700[2]	.001760

[1] Streaks of color and horizontal bands visible. S for normal coronas specially computed.
[2] Alternative, 11200, 3300.

Second Series.—$n_0=327000$. White (Electric) Light.

				× 10³	× 10³			
1	0	—	—			—	—	—
2	2	w p g	12.2	499	664	1.000	327000	.000305
3	4	w g p	11.8	458	606	.739	242000	337
4	6	w y v g	10.4	309	409	.545	178000	373
5	8	v ro g′	8.2	151	201	.397	130000	415
6	10	w g b r′	6.3	68.8	91.3	.279	91200	467
7	12	w br g|p	6.1	64.1	85.0	.184	60200	536
8	14	w br b g′p	4.7	29.4	39.1	.119	38900	620
9	16	N. coronas	4.0	17.6	23.4	.072	23600[1]	730
10	18	"	2.8	6.4	8.5	.026	8700[1]	.001020
11	20	"	2.0	2.4	3.1	.010	3300[1]	1410

[1] Alternative, 22200, 2800, 0.

Fourth Series.[2]—$n_0=546000$. White Light.

				× 10³	× 10³			
0	2	w′ r′	13.2	630	840	1.000	546000	.000257
1	4	w pv g′	11.2	390	518	.744	406000	285
2	6	w g p	11.6	434	561	.544	297000	315
3	8	w y pv g	9.7	251	333	.395	216000	350
4	10	w|o g	8.8	187	248	.288	157000	390
5	12	w br b	6.7	82.7	110	.206	113000	435
6	14	w y g	6.1	62.4	82.9	.138	75400	496
7	16	w br b g	5.1	36.6	48.5	.089	48600	575
8	18	w p g	4.3	21.9	29.0	.052	28700[3]	685
9	20	corona	3.5	11.8	15.7	.029	15800[3]	837
10	22	"	2.5	4.3	5.7	.010	5730[3]	.001170
11	24	"	1.6	1.2	1.6	.003	1640[3]	1780
12	26	"	lost					

[2] Cycles nearly absent. Third series omitted.
[3] Alternative, 25300, 10400, 4900, 0.

The green coronas reproduce the orders of nucleation already attributed to them, showing $n=90{,}000$, 110,000, 90,000, 90,000, a favorable result in view of the large differences of subsidence encountered.

27. *Smaller and larger pressure differences.*—To further elucidate the effect of the subsidence error and to exhibit the sequence of coronas more closely, experiments were now made with lower and higher exhaustions than the above. In view of the smaller steps of pressure, it was also thought that a more definite location of the cusps of the cycles would be possible. This, however, was not the case, for if the interval between observations is too small, the coronas are never free from distortion. Table 14 in particular, in which the interval is but one minute, gives evidence of this, but it is even present in the succeeding tables where the intervals are two minutes or more.

To reduce the data, the values of m must first be computed. If the latent heat of steam is considered constant (Regnault's value, 606 at 0° C.), and the ratio of specific heats is 1.41, the following values may be derived:

For $\delta p=22$; $\theta=10$	$m=4.2\times 10^{-6}$		For $\delta p=8.5$; $\theta=10$	$m=21\times 10^{-6}$
20	5.5		20	26
30	6.7		30	28

The effect of a rise of temperature on latent heat would be an increment of the order of .05 per cent. per degree. The specific heat ratio is also variable, and for lack of data applying to the region of low temperature in question these subsidiary variations must be disregarded.

If the data for $\delta p=17$ above be included, a table of double entry may be drawn up adapted for all pressure differences between 8 and 22 cm. and for temperatures between 10° and 30°.

The optic constant in the two cases becomes (since $n=6ms^3/\pi a^3$)

For $\delta p=8.5$ cm., $n=122s^3$ (diffraction) and $n=202s^3$ (subsidence).
For $\delta p=22$ cm., $n=284s^3$ (diffraction) and $n=470s^3$ (subsidence).

Finally the volume ratio, y, is at $\delta p=8.5$,

$$y=(57.7-8.5)/(75.6-17.9)=.853,$$

and at $\delta p=22$ cm.,

$$y=(73.7-22.2)/(76.0-2.3)=.700,$$

with which values a practical table is appropriately drawn up, time losses being ignored as above.

The subsidence constant computed for the different series shows the same falling off of value just before the coronas vanish, to which attention has already been called. The following cases may be instanced.

TABLE 12.—VALUES OF S FOR SMALL CORONAS.

	Low pressure, $\delta p=8.5$ cm.						Higher pressure, $\delta p=22$ cm.			
	s	S	s	S	s	S	s	S	s	S
	4.1–3.3	6.4	5.4–4.5	8.5	5.1–4.4	6.3	4.5–3.6	6.0	4.7–3.6	8.5
	3.3–2.6	4.6	4.5–3.6	8.1	4.4–3.6	6.3	3.6–2.7	5.1	3.6–2.6	5.5
	2.6–2.0	3.2	3.6–2.8	6.2	3.6–2.8	6.2	2.7–1.8	3.9	2.6–1.8	3.9
	2.0–1.1	3.4	2.8–2.1	3.9			1.8– .9	2.8	1.8–1.0	2.4
Probable $S=$		4.8		6.7		6.3		4.5		5.6
$\delta t=$		1^{m}		2^{m}		2^{m}		2^{m}		4^{m}

The means of the best values are in the five cases $S=4.8$, 6.7, 6.3, and $S=4.5$, 5.6, respectively, the mean of all of which is $S=5.6$. This value is practically the same as in the preceding table for $\delta p=17$ cm. The effect of waiting 2 or 4 minutes between observations does not appear in the individual results. The decay-effect of waiting 1 or 2 minutes is apparent, but this is due to the necessarily much more expeditious observation of coronas (time of fog suspension) in the former case. Curiously enough, at $\delta p=8.5$ cm. $S=6.5$ is larger than at $\delta p=22$ cm. where $S=5.0$.

The constants for computing diameters of fog particles ($d=\sqrt[3]{6m/\pi n}$) are at 8.5 cm., $10^2\times d=1.71n^{-1/3}$ and at 22 cm., $10^2\times d=2.27n^{-1/3}$. Thus at $\delta p=8.5$ cm. the ratio of distance between centers of cloud particles, $n^{-1/3}$, and their diameters is 58.4, and at $\delta p=22$ cm. the corresponding ratio is 44.0. It follows then that for the same corona, the distances apart are materially different in the two cases. Hence if the interstices enter into the character of the diffraction pattern and distribution of axial colors, these should be different for the two pressure differences in question.

TABLE 14.—CONSTANTS OF CORONAS. ARC LIGHT, CONDENSATION CHAMBER, AND DISTANCES AS IN TABLE 13. $\theta=21°$; BAROMETER, 75.6 cm.; $\delta p=8.5$ cm.; $y=.85$; $\beta=0$; $S=4.8$; $a'=.0034$; $a''=.0029$; $m=2.6\times10^{-6}$; $n_0=825000$; s MEASURED TO OUTER EDGE OF FIRST RING; PHOSPHORUS NUCLEI; $\delta t=1^m$.

z	t	Corona.	s	$n''=200s^3$	$N\Pi\ (1-\frac{S}{s^2})$	$n=n_0N\Pi$	$d=.0171\ n^{-1/3}$
	min.		cm.	$\times 10^3$			
−1	3	w y	13.0	440	1.17	965000	.000173
0	4	w o	12.1	354	1.000	825000	182
1	5	w c	12.1	354	.830	685000	194
2	6	w p	9.3	161	.690	569000	206
3	7	w v g	9.3	161	.554	457000	222
4	8	w bv g		—	.448	369000	239
5	9	w v b	9.8	188	.360	297000	256
6	10	w g p	9.0	146	.292	241000	275
7	11	w y g	8.8	136	.234	216000	285
8	12	w o b g	8.7	132	.188	155000	318
9	13	w o g	8.0	102	.150	124000	343
10	14	w r g	7.3	79.4	.119	98200	370
11	15	w c g	6.6	57.4	.092	75900	404
12	16	w g b r′	5.7	38.0	.070	57500	443
13	17	w g b r′	5.7	38.0	.051	41900	493
14	18	w br g	5.3	29.8	.037	30500	550
15	19	w r b p	4.5	18.2	.026	21600	617
16	20	corona	4.1	14.2	.017	14000	710
17	21	"	3.3	7.5	.009	7600 [1]	868
18	22	"	2.6	3.7	.005	3700 [1]	.001100
19	23	"	2.0	1.7	.002	1730 [1]	1420
20	24	"	1.1	.3	.000	200 [1]	2720

[1] Alternative 8580, 4130, 1150, 0.

TABLE 15.—CONSTANTS OF CORONAS. CONDENSATION CHAMBER AND DISTANCES UNCHANGED. ARC LIGHT; PHOSPHORUS NUCLEI; s TO OUTER EDGE OF FIRST RING; $\theta=21°$; BAROM., 75.6 cm.; $\delta p=8.5$cm.; $y=.85$; $\beta=0$; $S=6.7$; $a'=.0034$; $a''=.0029$; $n_0=110000$; $m=2.6\times10^{-6}$.

First Series.—$\delta t=2^m$.

z	t	Corona.	s	$n''=200s^3$	$NII\,(1-\frac{S}{s^2})$	$n=n_0NII$	$d=.0171\,n^{-1/3}$
	min.		cm.	$\times 10^3$			cm.
1	0	—		—	—		
2	2	w oy bg	10.5	235	1.000	110000	.000358
3	4	w o g	9.0	148	.799	87900	385
4	6	w c g	8.1	106	.627	69000	418
5	8	w g b r′	6.3	50.0	.478	52600	455
6	10	w o b[1]	5.6	36.0	.340	37400	510
7	12	w rp g	5.4	31.4	.229	25200	585
8	14	w br b g	4.5	18.8	.151	16600	670
9	16	corona	3.6	9.7	.087	9530 [2]	807
10	18	"	2.8	4.4	.039	4340 [2]	.001050
11	20	"	2.1	1.9	.017	1870 [2]	1390

[1] Seen very obliquely this changes to w g.
[2] Alternative 9530, 4040, 500.

Second Series.—$n_0=680000$; $S=6.3$; $\delta t=2^m$.

			cm.	$\times 10^3$			
1	2	w r′ } fog					
2	4	w r′ } fog	—				
3	6	w r′ } fog	—				
4	8	w o′	—				
5	10	w c	13.2	460	1.000	680000	.000195
6	12	w bv g	12.4	381	.824	560000	208
7	14	w vb g	11.8	329	.675	459000	222
8	16	w b g	11.0	266	.549	373000	238
9	18	w g p	10.7	245	.446	303000	255
10	20	w yg vp	10.2	212	.360	245000	273
11	22	w oy|g	10.1	206	.290	197000	294
12	24	w|o g	9.6	180	.232	158000	316
13	26	w r gy	8.6	127	.185	126000	341
14	28	w c g′	7.8	95.0	.145	98600	370
15	30	w g b p	6.4	52.4	.111	75500	404
16	32	w yg b p	5.9	42.2	.080	54400	451
17	34	w ro g	5.8	39.0	.056	37900	509
18	36	w br b|g	5.1	26.6	.038	26200	575
19	38	w y bg|r	4.4	17.0	.025	17100	663
20	40	corona	3.6	9.7	.014	9790	800
21	42	"	2.8	4.4	.006	4350	.001050

TABLE 16.—CONSTANTS OF CORONAS. CONDENSATION CHAMBER, DISTANCES, MEASUREMENT OF s UNCHANGED; ARC LAMP; $\theta = 24.5°$; BAROM., 76.0 cm.; $\delta p = 22$ cm.; $y = .70$; $\beta = 0$; $S = 4.5$; $n_0 = 360000$; $m = 6.1 \times 10^{-6}$; $a' = .0032$; $a'' = .00290$; PHOSPHORUS NUCLEI; $\delta t = 2^m$.

z.	t	Corona.	s	$n' = 360s^3$	$n'' = 470s^3$	$NII\ (1-\frac{S}{s^2})$	$n = n_0 NII$	$d = .0227\ n^{-1/3}$
	min.		cm.	$\times 10^3$	$\times 10^3$			cm.
1	2	w o'	—	—	—	—	—	—
2	4	w c'	—	—	—	—	—	—
3	6	w g'|p'	13.2	828	1080	1.000	360000	.000320
4	8	w y|vb	10.5	421	550	.683	246000	362
5	10	w c g'	8.5	221	289	.456	164000	415
6	13	wg b|p	6.0	79.6	104	.297	107000	478
7	15	w ro g'	5.9	73.8	96.3	.183	65900	562
8	17	w y o b	4.5	33.9	44.3	.111	40000	664
9	19	w br b	3.6	16.8	21.9	.061	22000[1]	810
10	21	corona	2.7	7.1	9.3	.026	9290[1]	.001080
11	23	"	1.8	2.3	3.0	.008	2920[1]	1590
12	26	"	.9	.3	.3	.001	360[1]	3200

[1] Alternative 22000, 10500, 2660, 0.

SECOND SERIES.—$n_0 = 410000$; $S = 5.6$; $\delta t = 4^m$.

	min.		cm.	$\times 10^3$	$\times 10^3$			cm.
1	4	w v	12.7	738	963	1.000	410000	.000305
2	8	w g|v	10.1	371	484	.675	277000	350
3	12	w r g	8.8	245	320	.444	182000	400
4	16	w g b|p	6.3	90.0	117	.287	118000	462
5	20	w r g	5.8	70.2	91.7	.173	70900	548
6	24	w y b g	4.7	37.4	48.9	.101	41400	656
7	28	corona	3.6	16.8	21.9	.053	21600	814
8	32	"	2.6	6.7	8.7	.021	8690[2]	.001100
9	36	"	1.8	2.1	2.7	.007	2790[2]	1610
10	40	"	1.0	.4	.5	.001	490[2]	2900

[2] Alternative 8690, 1230, 0.

28. *Remarks on the tables.*—Considering the graph, figure 10, corresponding to table 14, it is seen that the curve as a whole lies above the locus $n' = 200s^3$. This might be rectified by using a larger value of S than the small one ($S = 4.8$, while the mean value is 5.6) specially computed. The divergence of the S-effect is enhanced in view of the large number of exhaustions.

The graph $n = n_0 NII$ brings out for the first time the cycle of the first color series, w y to w p, which in the shorter apparatus above was not fully attainable. The successive colors of the first annuli vary in the order of wave length, though nothing was observed above the first w y. The next color cycle (enlarged 10-fold in the adjoining curve) is very complete, though irregular from the inevitable color distortion, the interval between observations being but one minute. The following color cycles III and IV, which include the vivid annuli, manifest the same relations already instanced above. The small value $n=70{,}000$ which belongs to the green corona, and the correspondingly small values for the other coronas, are in accord with the small pressure difference, $\delta p=8.5$, chosen; but it will presently appear that this value is even smaller than would be predicted. The crests of the n-cycles may be located at $n=25{,}000$, $65{,}000$, and $550{,}000$, from which the corresponding d-values would be $d\times10^6=585$, 430, 210 cm., indicating diameters of fog particles in the ratio of 3:2:1.

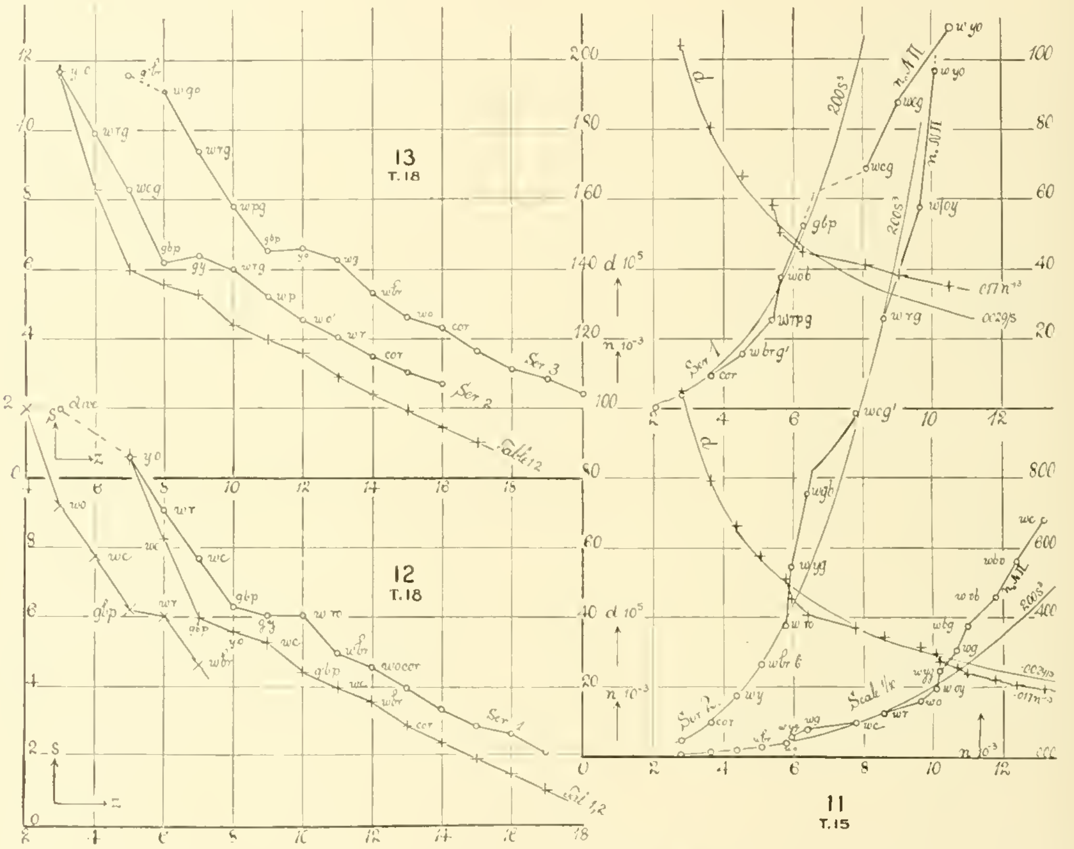


FIGURE 11.—CHARTS FOR TABLE 15, SHOWING THE NUCLEATIONS (n) AND DIAMETERS (d) OF THE FOG PARTICLES, IN TERMS OF THE APERTURES (s) OF THE CORONAS.

FIGURES 12, 13.—CHARTS FOR TABLE 18, SHOWING THE RELATION OF THE APERTURES, s, OF THE CORONAS TO THE NUMBER, z, OF EXHAUSTIONS.

The d-values are much more difficult to correlate, although the main cycles are apparent. The appearance here is that of four independent loci which appear united as the result of color distortion. The view which ascribes to these curves different parameters is in many respects plausible. There are three green coronas discernible corresponding to $10^6\times d=275$, 443, 617, about in the ratio of 3:5:7. But this result is again merely tentative.

Table 15 contains two series of results in which larger times intervene between the exhaustions to insure more thorough diffusion and less distortion of color. The data are mapped out in the same chart, figure 11, one above the other. In the n-curves four cycles may be made out, the lower less distinctly, as this is concealed in a measure by the specially computed S-values. There is reasonable agreement with the graph $200s^3$, though the upper cycle lies above it. In the d-curves the agreement with $.0029/s$ is throughout as close as the difficulty of observation permits. Three sweeping marches from violet to deep red may be distinguished.

In the last table (16) high pressure differences $\delta p = 22$ cm. are brought to bear, and the time intervals $\delta t = 2$ and 4 minutes intervene between the exhaustions. A definite effect of the latter does not appear, since the nucleation of the green coronas, for instance, is $n = 107{,}000$ and $118{,}000$, with more nuclei indicated for the larger time interval. The reverse would be the case if there were marked time loss. The corresponding charts may be drawn to show the relations in detail. The curve $470s^3$ lies above the higher coronas, whereas in the preceding cases it lay below them, indicating the difficulty encountered in computing sufficiently correct values for the subsidence constant, S. While the n-values show the usual relations, the d-values are more difficult to interpret; but three cycles may be made out, with the middle one unusually bulging and contracted.

29. *Nucleation of the green coronas.*—These values, though difficult to obtain and suffering from cumulative errors, are nevertheless consistent; and the nucleation to produce the green corona seems to depend on the distance between particles. Put $d/n^{-1/3} = D$. Then the above results show that $n = 10^7(D - .0114)$. Hence if the distance of particles is 87 times their diameter the green coronas should appear for vanishing nucleations. This implies a limit of values of n by which green coronas may be evoked. Furthermore, since the apertures of this type of coronas remain within a range of values nearly the same for all conditions of nucleation, the value of n may be found below which green coronas do not occur. For the diameter of fog particle is here about $d = .00046$ cm., and therefore $n = 15{,}300$. One may argue, therefore, that at least 15,000 nuclei per cubic centimeter must be present if coronas of the middle green type are to be possible.

TABLE 17.—NUCLEATION OF THE GREEN CORONAS.[1] n (computed) $= 10^7\ (d\sqrt[3]{n} - .0114)$.

Table.	$n \times 10^{-3}$	δt	Table.	$n \times 10^{-3}$	δt	Table.	$n \times 10^{-3}$	δt
		min.			min.			min.
14	49.7	1	13	89.1	2	16	107	2
15	52.6	2	13	110.0	2	16	118	4
15	75.5	2	13	91.2	2			
			—	94.2	2			
Mean	57.0		—	96.1			113	

$10^5 d =$	45 cm. (obs.)	46 cm.	47 cm.
$\delta p =$	8.5 cm.	17 cm.	22 cm.
$d\sqrt[3]{n} =$	.017	.021	.023
$10^{-3} n =$	57 (comp.)	96	113

[1] Earlier values, $\delta p =$ 17 cm. and cubical vessel, $10^{-3}n = 85$, 106, 104, 96, and 96, 96, the mean being $n =$ 97000.

While these inferences are essentially uncertain and might even seem attributable to the time coefficient, β, neglected, the observations do not warrant such exception. Thus at $\delta p=22$ cm. and $\delta t=4$ minutes, the total time consumed was 36 minutes, whereas in the case of $\delta p=8.5$ cm. it was only 32 minutes for $\delta t=2$ minutes, and only 21 minutes for $\delta t=1$ minute. The total amount of time loss must therefore actually have been smaller in the latter cases.

OTHER CAUSES OF CHANGE IN THE TYPES OF CORONAS.

30. *Thickness of cloud layer.*—In passing from the cubical to the long apparatus, the thickness of the cloud layer decreased from 20 to 16 cm. On tipping the former vessel on its trunnions, and looking through the chamber diagonally, the thickness of cloud layer could be increased to 30 cm. In all these cases, the type of corona and its diameter showed no appreciable change. If symmetry about the center is maintained, the effect of the thickness of the cloud layer seems thus to be absent.

31. *Obliquity of diffraction.*—When the direction of the diffracted ray differs by a small angle from the direction of the normal ray of light, the type of corona does not change as to color of annuli. If, however, the angle of deviation due to diffraction is very large, the corona may change in character. Thus for great obliquity the orange-red corona was found to change into the preceding green corona. In other words, a larger particle on very oblique diffraction may produce the same corona as a smaller particle on less oblique diffraction.

32. *Effect of wave length.*—Since at $\delta p=17$ cm., $a=73\lambda$, and therefore $n=6ms^3/\pi a^3=6\ ms^3/\pi\lambda^3(73)^3=23s^3/10^{12}\lambda^3$, the equation for different colors would be (denoting the colors by subscripts) $n=67s_c^3=97s_r^3=107s_o^3=118s_y^3=154s_g^3=221s_b^3=360s_v^3$, etc., while for other pressure differences the same relations would be preserved.

Testing this by the very full series in the second part of table 15, and remembering that the measurement is made to beyond the first ring, the following data may be deduced:

$s=1030$	w oy (p) g	n (observed) = 197000	n (computed) = 186000
636	w r g′	126000	126000
262	w g b p	75500	75200

If the w r g′ corona is taken as correct, the w g b p corona will also be, as well as the w oy (p) g corona. But in the latter case the narrow purplish ring which intervenes before the green and the general difficulty of defining the mixed colors of the second ring makes inferences of the present kind precarious. Nevertheless it is probable that the rather sudden transition of green to blue in the colors of the second ring is associated with the underlying cause of periodicity. Examples of this kind might be multiplied.

DIFFERENT SPEEDS OF EXHAUSTION FOR THE GIVEN PRESSURE DIFFERENCE.

33. *Increased suddenness of condensation.*—As a final test of the trustworthiness of the above sequences, it was necessary to repeat the results with some form of valve more nearly instantaneous in its action. In the case of air nuclei, special comparisons instanced below (Chap. IX, § 3) showed that for a reasonable relation between the sizes of the condensation chamber and the vacuum chamber, an ordinary plug stopcock was quite as serviceable as an instantaneous valve, the coronas observed with the air nuclei being in both cases the same. With phosphorus nuclei and at the outset of the experiment, however, this is not quite the case, at least when the nuclei are very numerous and very small.

The design of the new valve was very simple. In figure 3, p. 58, *V* leads to the vacuum chamber (large aspirator flask), and *C* to the condensation chamber.

TABLE 18.—THREE GEOMETRICAL SEQUENCES OF CORONAS, FOR INSTANTANEOUS VALVE. CHAMBER, $20\times 26\times 35$ cm.^{3}; DISTANCES, 85 AND 250 cm.; $\theta=22°$; BAROM., 74.9; $\delta p=17$ cm.; $y=.767$; $\beta=0$; $S=2.1$; $S'=1.95$; a (SUBSIDENCE) $=.0029$; $m=4.8\times 10^{-6}g$; $n'_0=308000$; $n_0=340000$; PHOSPHORUS NUCLEI; WELSBACH LAMP, AND s MEASURED TO OUTER EDGE OF RED RING.

FIRST SERIES.

z	t	s	Corona.	$n'=376s^3$	$N\Pi\,(1-\frac{S}{s^2})$	$d=.021\,n^{-1/3}$	n'	$N\Pi'$
0	min.	cm.	Nucleation.	$\times 10^3$				
1	1		fog					
2	4	(13.0)	w r′					
3	7	(11.0)	olive					
4	10		g′ r′					
5	13	10.6	y o bg	534	1.000	.00030	308000	1.000
6	17	9.1	w r g′	288	.752	33	232000	.754
7	20	7.7	w c g	171	.562	36	174000	.564
8	23	6.3	g b p	94.0	.416	40	129000	.419
9	26	6.1	gy br b′	85.3	.302	45	93900	.305
10	29	6.1	w ro g	85.3	.218	50	68100	.221
11	32	5.0	w br cor	47.0	.158	56	49600	.161
12	35	4.6	w o cor	36.6	.111	62	35100	.114
13	38	4.0	corona	24.1	.077	71	24600	.080
14	41	3.4	"	14.8	.051	81	16300	.053
15	44	2.9	"	9.7	.032	94	10500	.034
16	47	2.6	"	7.0	.019	.00112	6200	.020
17	50	2.1	"	3.5	.010	.00140	3400	.011
							Note: $n'_0=$ 321×10^3	
							303	
							278	
							285	
							345	
							313	
						Mean:	308000	

R is a soft rubber cork which can be raised or suddenly lowered (in the latter case by the blow of a swivelled hammer not shown in the figure) by actuating the knob or handle at the upper end of the rigid rod *r*. There is a stuffing box at *S*. The end of the tube *p* has been turned off smoothly and serves as a seat for the plug, *R*. Stiff glycerin is used as a lubricant. All passageways and pipes are wide, the latter at least one inch in diameter. The valve has retained its efficiency after countless experiments, but it must be left open when not in use.

34. *Results.*—The results are given in table 18, on a plan similar to the above tables, and the calculations are made in the same way. All operations were strictly timed, and it was thought best to compute *S* from subsidence as

$$S' = s_z^2(1 - \tfrac{1}{y}(s_{z+1}^3/s_z^3)).$$

The corresponding n_v is written n'_v. The result is $S' = 1.95$. Computed from the observations themselves, $S = 2.1$, 1.7, for instance, in the first two parts of the table, a difference which can only be explained on the ground of observational error. Usually 3 minutes were consumed by the operations between the exhaustions, while the fog was dissipated (by the influx) within 15 sec. after the exhaustion. In the last series but 2 minutes are allowed between the observations, but there seems to be no appreciable difference in the data so far as this cause is concerned.

Second Series.—$\theta = 24°$; barom. = 75.08 cm.; $\delta t = 3^m$; $y = .767$; $n_o = 212000$; $n'_v = 305000$; $m = 5.0 \times 10^{-6}$g/cm³; $S = 1.7$; $S' = 1.95$.

z	t	s	Corona.	$n' = 376s^3$	$N\,\Pi\,(1-\frac{S}{s^2})$	$d = .021\,n^{-1/3}$	n'	$N\,\Pi'$
1	43		fog	$.390 \times s^3 = 10^{-3}n'$				
2	45	(13)	w r′	—				
3	48	(12)	b′ B	—				
4	51		g B	—				
5	54	11.7	y′ o	624	1.000	.00031	305000	1.000
6	57	9.9	w r g	378	.758	34	231000	.756
7	60	8.3	w c g	223	.571	38	173000	.568
8	3	6.2	g b p	92.8	.427	42	129000	.423
9	6	6.4	g y | b′	102.2	.313	46	93900	.308
10	9	6.0	w r g	82.4	.230	51	68600	.225
11	12	5.2	w p cor	55.0	.168	57	49700	.163
12	15	4.5	w yo cor	36.8	.121	64	35400	.116
13	18	4.0	w br cor	25.9	.085	72	24700	.081
14	21	3.5	corona	16.7	.059	83	16500	.054
15	24	3.0	"	11.0	.038	96	10500	.035
16	27	2.7	"	5.5	.024	.00115	6400	.021
							Note: $n'_v =$	
							317×10^3	
							320	
							310	
							315	
							265	
						Mean:	305000	

THIRD SERIES.—$\theta = 24°$; barom. $= 75.08$ cm.; $\delta t = 2^m$.

z	t	s	Corona.	$n' = 376s^3$	$N\,\Pi\,(1 - \frac{S}{s^2})$	$d = .021 \times n^{-1/3}$	n'	$N\,\Pi'$
1	40		fog					
2	42		w r′					
3	44	(13)	w p					
4	46	(12)	olive					
5	48	(11)	g′ r′					
6	50	11.1	w y o	540	1.000	.00030	346000	1.000
7	52	9.4	w r g	324	.750	33	255000	.739
8	54	7.8	w p g	185	.558	36	196000	.566
9	56	6.5	g b p	107	.408	40	145000	.420
10	58	6.6	y o	112	.293	44	106000	.307
11	60	6.2	w c g	95.2	.210	49	77800	.225
12	62	5.3	w br	58.1	.150	55	56700	.164
13	64	4.6	w o cor	38.1	.111	61	40500	.117
14	66	4.3	corona	31.2	.070	69	28400	.082
15	68	3.6	"	18.2	.046	78	19400	.056
16	70	3.1	"	11.5	.028	90	12600	.0364
17	72	2.8	"	8.54	.0153	.00107	7700	.0223
18	74	2.4	"	5.38	.0035	127	4500	.031
							Note: $n_0' =$	
							323×10^3	
							380	
							325	
							320	
							383	
							(420)	
						Mean:	346000	

n' and S' computed from subsidence and time.

To compare the new observations with the older ones above, it is convenient to lay off the aperture, s, in terms of the order of the exhaustion, z, as has been done in the charts, figures 12 and 13. The following peculiarities are observed: Below the g-b-p coronas ($s = 6$ to 6.5 cm.) the general slope of all the curves is nearly the same. Above these coronas, the older results obtained with the plug valve correspond to a decidedly steeper slope than the new results. Curiously enough, therefore, a greater number of exhaustions are required in the case of the instantaneous valve to pass from a given corona to a given succeeding corona than in the case of the stopcock. The instantaneous valve thus removes a smaller relative number of nuclei per exhaustion than does the stopcock, so long as fresh nuclei or great numbers are in question. Subsidence of fog for the very fine particles here in question need not be considered in explanation. In fact, the recent work is even more rapid than the old.

35. *Growth of nuclei.*—The simplest way of accounting for this result is to assume that there is a continual growth of nuclei in the interval between the observations, whereby those of extreme smallness come first within the range of action of the instantaneous valve. The excess of available nuclei obtained

in this way would gradually decrease toward the end of the experiment so that the slopes of all curves compatibly with the observations would gradually be the same. Below the middle g-b-p corona, the curves if placed together would nearly coincide. The difficulty with this hypothesis is the absence of any obvious effect when the time between observations is varied. The curves are about the same for $\delta t = 2$ min., 3 min., or even 12 min., so far as observed.

36. *Subsidence.* The effect of errors in the subsidence constant may be estimated. Writing the equation $n_z = n_0 10^{(z-Z)\log y} \Pi$, in the approximate form $n_z = n_0 10^{(z-Z)\log y}\left(1 - S\left(\frac{1}{s^2_z} + \frac{1}{s^2_{z+1}} + \frac{1}{s^2_{z+2}} + \right)\right)$, whence if $N = 10^{(z-Z)\log y}$, $\delta n_z = n_0 N \delta S \Sigma\left(\frac{1}{s^2}\right)$.

It is preferable to use the inverse method, putting $n_0 = n_z / N\left(1 - S\Sigma\left(\frac{1}{s^2}\right)\right)$, whence $\delta n_0 = \frac{n_z}{N}\Sigma\left(\frac{1}{s^2}\right)\delta S$.

Putting $n_z = 10500$, $n_0 = 212000$, $N = .0703$, $\Sigma\left(\frac{1}{s^2}\right) = .265$,

$$\delta n_0 = 40000\,\delta S, \text{ nearly.}$$

Thus if $\delta S = .2$, $\delta n_0 = 8000$, or relatively $8000/212000 = .038$. It follows that by the error of .2 made in the estimate of S, n_0 will not be affected more than about 4 per cent., which in no way accounts for the observed discrepancy of the new and the old results.

37. *Exhaustion ratio.*—Again if the above value of n_0 be taken, the effect of an error in the exhaustion ratio y will be

$$-\delta n_0 / n_0 = \frac{n_0}{y}(z - Z)\delta y.$$

For $n_0 = 212000$, $z - Z = 15 - 5$, $y = .767$, an average case in the preceding table, $\delta n_0 / n_0 = 13\delta y$, or for

$\delta y = .1$	$-\delta n_0 / n_0 = 130\ \%$
.05	65 %
.01	13 %

showing that great care is needed in relation to y.

38. *Inferences.*—To reach an opinion as to the cause of the observed initial diversity of rates one may note that for equal pressure differences, smaller nuclei are necessarily caught by the instantaneous valve than by the stopcock. More nuclei are thus within reach in the former case: but apart from this, since all other conditions are the same for both cases, the rate of denucleation should be the same, even if the absolute number of efficient nuclei removed by exhaustion is greater for the instantaneous valve. If therefore one begins with the same corona which implies identity of diameter of particle and may be assumed to imply an identical number of available or effective nuclei in both cases, the two curves should be identical. In figures 12 and 13, considered first between the upper w-y-o and the middle g-b-p corona, the new and the old curves cross at the large w-y-o corona. If under identical exhaustions the number of available nuclei are therefore successively greater for the instantaneous valve

than for the stopcock, there must be an accession of nuclei between the exhaustions in the former case or a loss of nuclei for the case of the plug.

Between the middle g-b-p corona and dust-free air, nuclei are removed at the same rate in the two cases, as the curves here have practically the same slope and would be brought to coincidence throughout if the upper coronas were to coincide. Inasmuch as in the case of atmospheric air the g-b-p corona is not exceeded, it is thus immaterial which form of valve is used, and the direct experiments of Chapter IX bear this out.

The alternative that nuclei are generated by very sudden expansion is without correlative evidence. At least all my experiments to detect ionization produced by sudden expansion have failed. It is equally difficult to account for an abnormal loss of nuclei in the earlier stages of the experiment of table 18. True, it is here that the ionization of phosphorus vanishes, though this evanescence is enormously rapid by comparison.

The nucleations of the g-b-p corona are by table 18, $n=129{,}000$, $129{,}000$, and $145{,}000$, respectively, values decidedly larger than were found above, and due to the greater geometrical remove of the normal coronas from the g-b-p corona. As about one more exhaustion is required on the average in the new data, the corresponding results for the same s would be, $n=94{,}000$, $94{,}000$, $106{,}000$, which agrees with the order of values above.

39. *Different rates of exhaustion for moderate nucleations.*—In this place it is interesting to insert a series of direct comparisons on the number of nuclei within the reach of a half-inch exhaust pipe with an ordinary plug stopcock, and the number caught when the valve is as in figure 3 with all pipes over one inch in diameter and less than one foot long. These are given in table 19, the

TABLE 19.—DIRECT COMPARISON OF RESULTS FOR STOPCOCK .5″ DIAMETER, AND INSTANTANEOUS VALVE 1″ DIAMETER. LARGE CONDENSATION CHAMBER, AIR NUCLEI. $\delta p=17$ cm.

Experiment No.	Remarks.	Corona.	s	$n=375s^3$
			cm.	
1	Stopcock	w c g′	5.5	62000
2	" "	g b p	5.9	77000
3	" "	g′ b p	5.8	73000
4	" "	g b p	5.7	69000
5	Inst. valve	w p	6.9	124000
6	" "	w p	6.9	124000
7	" "	w p	6.9	124000
8	Stopcock	w p	6.4	98000
9	" "	w p	6.7	112000
10	" "	w p	6.8	118000
11	Inst. valve	w c g	7.3	149000
12	" "	w cg	7.1	137000
13	" "	w c g	7.2	140000
14	Stopcock	w c g	7.2	140000
15	" "	w c g	7.3	149000

data for the stopcock alternating with data for the instantaneous valve. Unfortunately, the time intervals between observations were not quite equal, as the necessary adjustments consumed varying amounts of time.

These data are shown graphically on the chart, figure 14, p. 83, the abscissa being merely distributive. If the mean data of each set be taken the results are

for the stopcock: $s=6.57$, $s^3=284$,
for the inst. valve: $s=7.04$, $s^3=349$,

or the ratios of s^3 are about .81. Since, however, in view of periodicity, the g-b-p coronas show abnormally small values of s, it is better to compare the red coronas only. In this case the mean values are

for the stopcock: $s=7.0$, $s^3=343$,
for the inst. valve: $s=7.2$, $s^3=373$,

or the ratios of s^3 are .92. Hence the two valves differ as to their data by less than 10 per cent. If this value be ascribed by the value of m assumed it would not suffice for the values obtained by photography.

In table 18 the ratios of s^3 for the large crimson coronas under like occurrence were on the average .42, widely different from the present, showing that the discrepancy in table 18 enters with the very small nuclei of the very large coronas.

One may note that the nucleation of the large room is gradually increasing, due to a single small gas burner (source of light), although the air was all pumped into the condensation chamber from the floor of the room.

40. *Conclusion.*—As none of the explanations given are satisfactory, it seems well to restate the case in conclusion with additional remarks on a possible explanation. No matter which group of sizes of nuclei are efficient in producing coronas, the effect of successive identical partial exhaustions must be to reduce the numbers by the same *relative* amount. If a given corona is obtained for the slower and the faster exhaustion for the same pressure difference, etc., it may be assumed for argument that the same number of efficient nuclei must occur in both cases, though they may not be the same nuclei as to size. It follows that the same corona should occur in the two cases in each of the successive exhaustions. This is only true below the middle g-b-p corona, *i. e.*, for relatively fewer nuclei (nucleation below about 100,000 per cub. cm.). In this region of distribution, both valves eventually remove all nuclei, and they remove them at the same rate.

For nucleations above 100,000, however, proportionately more nuclei are apparently removed by the slower exhaustion, *cœt. par.*, than by the faster exhaustion, so far as coronal evidence is in question, precisely as if the faster exhaustion were itself productive of nuclei (as, for instance, by breaking up coarser into finer aggregates). One may note, moreover, that in this stage of the work, the phosphorus nuclei are at first ionized. Subsidence is without effect.[1]

It is just here that another important question is suggested which may perhaps offer evidence in explanation. It was shown above (§ 8, table 2) that the moist air after exhaustion very nearly regains its original temperature after the lapse of even half a minute, while the coronas persist throughout this interval and much longer without appreciable change of character. It is difficult to understand why the fog particles do not evaporate proportionately to the rapid rise of temperature, unless there is rapid evaporation and diffusion from the relatively *warm* inner surface of the walls of the condensation chamber, immediately after exhaustion. In any case, the method above used for computing m, the moisture precipitated per cub. cm., will give a result too large, for it takes no account of the rapid increase of temperature in question after the fog particles are produced. The swifter the exhaustion the larger this discrepancy (which is probably indeterminable) is liable to be. Thus in the above case for the pressure difference $\delta p = 17$ cm., at 20°, the cooling ideally as far as $-9.6°$, rises to 8.8°, in consequence of condensation of fog particles, but within $\frac{1}{2}$ minute the temperature is nearly 20° again. Hence the precipitated 4.6×10^{-6}g/cm³ at 8.8° is to remain undisturbed while the moisture content of saturated air rises from about 8.7×10^{-6} at 8.8° to about 17.2×10^{-6}(g/cm³) at about 20°, leaving an actual deficit of about 4×10^{-6}g/cm³. This would be out of the question unless moisture evaporated immediately from the damp and warmer walls and the pool of water in the bottom of the apparatus to supply the deficiency. But these conditions are vague, for this moisture may actually be precipitated on the colder fog particles. To some extent, therefore, a degree of uncertainty is left in the determination of m, the moisture precipitated per cub. cm., inasmuch as the actual temperature at which the fog particles persist, and to which they have accommodated themselves, is left in doubt.

It is well to observe, however, that as there will presumably be more evaporation from the fog particles while the normal air temperature is being regained in case of very rapid than for the slow exhaustion because lower temperatures are in general associated with the former case, the discrepancies of plates 12 and 13 above the g-b-p corona may possibly be explained in this way. Compatibly with observation the effect would be less marked as the fog particles are larger. Finally, very large coronas are always more fleeting in character.

Experimentally and with a bearing on Chapter IX the question is easy of decision. So long as the pressure difference corresponding to the lower limit of spontaneous condensation of moisture from dust-free air is not approached (it will usually be reached at about $\delta p > 20$ cm. for the above types of appa-

[1] Recent experiments have shown that the very small nuclei associated with larger nuclei evaporate their loads of water after condensation in such a way as to form water nuclei. As the latter must be larger than the original nuclei now held in solution, a reason for the excess of nucleation detected by the instantaneous valve is suggested.

ratus), and so long as the g-b-p corona is not exceeded (which again is the actual case), the degree of rapidity of condensation on the usually occurring atmospheric nuclei is a matter of little consequence. Thus the same coronas appear with non-filtered atmospheric air, *cæt. par.*, both for the $\frac{1}{2}$-inch plug valve and for the 1-inch instantaneous valve, even for large variation in the size of the condensation chamber.

CHAPTER VII.

I. MICROMETRIC MEASUREMENT OF FOG PARTICLES.

Earlier Methods.

1. Before using the data computed for the dimensions of fog particles in the reductions of my observations of atmospheric nucleation, it seemed expedient to endeavor to obtain corroborative values by some straightforward method. Aitken's dust counter had naturally suggested itself early in the course of my work; but the results so obtained are essentially indirect, as the fog particles are not themselves observed. It was necessary, therefore, to devise apparatus by which the identical fog particles of a given corona could be directly entrapped and held for examination. This was eventually accomplished in a way admitting, apparently, both of the measurement of the diameters of the particles and of counting the number precipitated under known conditions. Moreover, the particles caught, however fine (even less than .0003 cm. in diameter), can often be kept in place for observation for some time, so that microscopic photography would appear to be at once applicable not only for the purpose of obtaining size but number.

Many investigations are thus suggested, as, for instance, a repetition of Thomson's method for determining the charge of an ion. Again, while the corona gives merely the average size of the cloud particles, the microscope is particularly available for indicating variations of diameter for the particles of the same corona. In fact, the water particles of the coronas as caught on the plate are not of a size; they are graded, and hence the nuclei are probably also graded in size.

2. *Apparatus.*—Aitken's beautiful and highly ingenious instrument is well adapted for the purposes for which it was designed. Apart from this, it will furnish only an estimate of the dust contents sought. The droplets evaporate too rapidly, and are often too numerous for exact counting. The need of mixing atmospheric air with dust-free air with shaking and stirring is an interference with the nucleation. In fact, water nuclei may even be generated in this way, possibly by the friction of air passing across damp surfaces. There is the tendency of the plate after long use to fog permanently or to collect droplets on its own account. Finally, it would be very difficult to remove the contents of the coronal chamber to the dust-counter without reducing the nucleation during the transfer.

I therefore endeavored to ascertain whether the particles might not be made visible directly. The chances of success seemed small indeed, particularly as Assmann had failed to see the particles with magnifications of even 400 diameters. But after long trial, the result was eventually accomplished in a way that now seems surprisingly simple.

The compound microscope, *M*, magnifying about 100 diameters, is provided with a filar ocular micrometer, *n*. The objective and the whole lower part of the microscope is submerged in the condensation chamber, being suspended for this purpose from the wide rubber cork, *C*. All lenses below *C* are hermetically sealed with wax. The microscope originally carried a rigid stem, *r*, to which were attached the plate, *s*, to be examined, the mirror, *m*, and the metallic disc or shield, *p*. Afterwards the more flexible adjustment shown in the figure and described below was adopted. The lower side of *p*, which is flush with the objective, and the upper side of *s* are covered with wet blotting-paper, the latter being perforated to admit light into the microscope through the thin cover-glass placed at *s* and held sharply in focus by a suitable clip. The field within which drops are to be counted is bounded at pleasure by the wires of the micrometer.

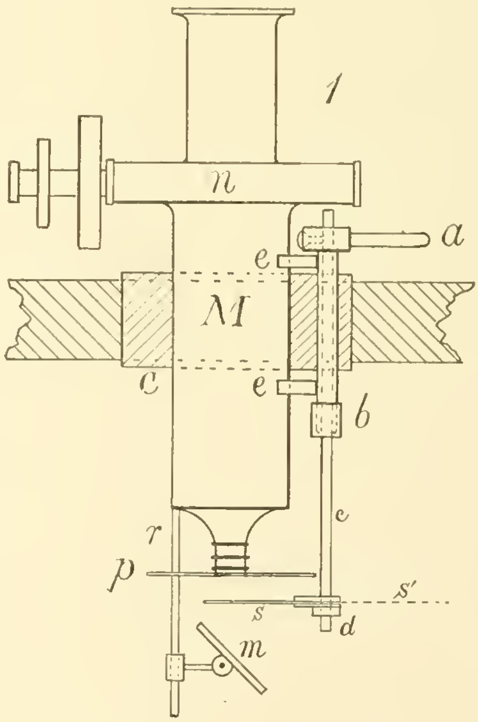


FIGURE 1.—MICROMETRIC APPARATUS.

This apparatus was totally unsuccessful. Drops were but rarely seen to fall on exhaustion, while the dew soon gathered on the plate, *s*, in such a way as to be easily mistaken for droplets; for the dew evaporates like the latter when the microscope is removed, and the regularity of the pattern on the plate is the only distinguishing feature.

Various modifications of this apparatus were then used, among them capsule forms, figures 2 and 3, similar to Aitken's, but containing a very thin plate of glass or mica or celluloid slightly raised above the base on pellets of wax. It was supposed that this would counteract the tendency of the drops to vanish by evaporation from the warmer glass surface. Capillary metallic tubes led to the curl aneroid, *a*, the filter, *f*, and to the cock for influx of air, the only large

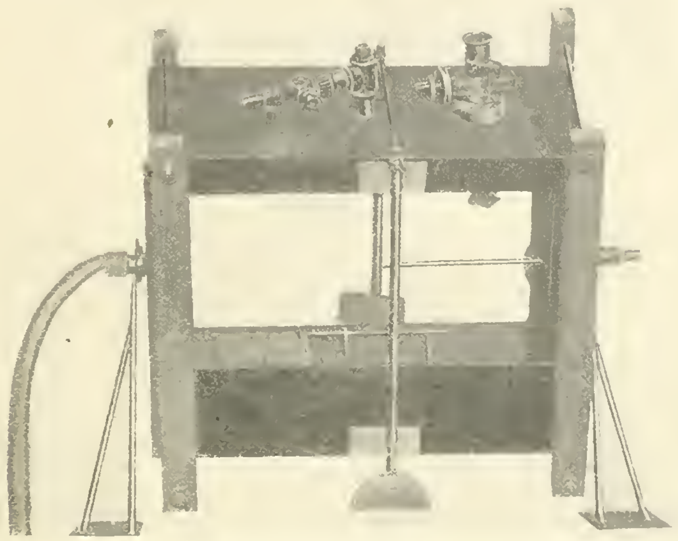


FIGURE 1*a*.—THE SAME MOUNTED IN CONDENSATION CHAMBER.

tube being the exhaust pipe, *e*. Condensation again occurred as a microscopically granular deposit spontaneously on the raised surface, under all circumstances, and the experiments were failures. After oiling the filmy mica surface, *p*, however, droplets were often seen to fall and either to stick fast or to float. These could at times be counted (2000–5000 per cub. cm.); but the rapid evan-

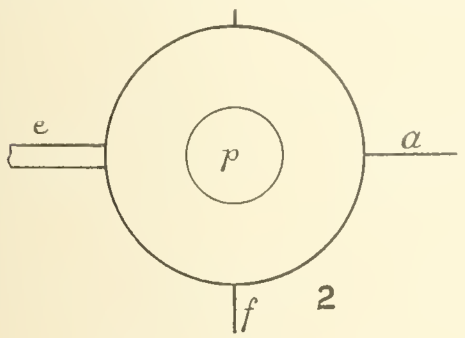


FIGURE 2.—CAPSULE. PLAN.

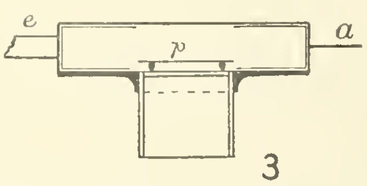


FIGURE 3.—SAME. SECTIONAL ELEVATION.

escence of precipitated droplets and the failure of all attempts to reach systematic results induced me to abandon the capsule.

I therefore returned to the apparatus in figure 1, using at *s* a plate of thin microscopic glass covered with a thin film of oil and exposed in the capacious vacuum chamber. The experiments were now phenomenally successful. Thus for the aperture $s = 5$ the mean results were $n = 150000$, and for $s = 4.6$ (w g b p), $n = 140000$. The precipitation of globules was clearly seen, and they persisted even after the exhaustion was removed. The numbers being excessive and referable to globules swept in by lateral air currents, an improvement was now added by increasing the diameter of the disc p to about 5 cm. The improved apparatus gave no results whatever, and the mere addition of the wider disc wiped out all precipitation. But this capricious behavior is characteristic, for next day drops were seen to fall as follows:

$s = 4.5$	w g b p	$n = 6.5 \times 10^4$.
4.6	w g b p	4.7
6.3	w g b p	13.3

after which no precipitation could be caught in the 6 subsequent exhaustions by the identical method. The same unaccountable irregularity was noted in the afternoon. Next day the first experiments showed

$s = 6.0$	w c g	$n = 7.3 \times 10^4$.
6.4	w g v p	12.0
	etc.	

after which further precipitation did not occur.

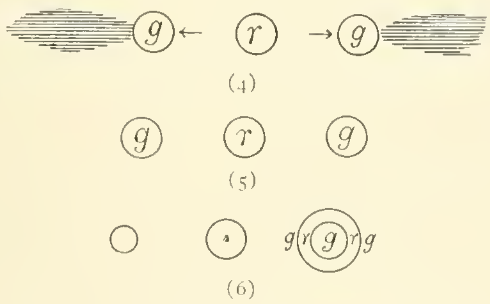
The apparatus was then again modified to the final form shown in figure 1, by inserting a thin brass tube laterally through the stopper, C, and firmly soldering this tube above and below at c to the body of the microscope. A rod snugly fitting this tube thus provided an eccentric focussing device, *abcd*, with a stuffing box at b, and an external handle at a. The latter is adjustable by aid of a set screw so that the plate s may be kept in focus during rotation of the rod. To catch the droplets, the plate s is rotated into the position s' quite beyond the shield, for a definite time (15–30 seconds), and then returned to s for examination. In this way the definite results were obtained, in a manner to be further detailed below, with the apparatus free from capricious behavior. It is of particular interest that the particles caught on the oiled surface persist as brilliant round globules for a long time (sometimes 10 min. or more) in a saturated atmosphere. They very gradually vanish as a rule on the readmission of air into the condensation chamber.

To remove the globules for the next experiment, the influx of air is thus not always sufficient. It is necessary to withdraw the microscope from the condensation chamber bodily and to wave it about a few times in dry air. On returning it to the chamber the plate is then again clear and white.

At first the plate was oiled by a small flat piece of blotting-paper saturated with oil and held on a stem, care being taken to remove all excess. Clean machine oil or ordinary illuminating oil or a mixture of the two subserved the purpose about equally well. Probably the best method of oiling consists in dipping the plate rotated outward to s' in very hot melted vaseline (to drive away moisture), removing the excess while hot by filter paper and when cold submerging the plate in petroleum for transparency. With solution of vaseline in benzine, etc., I have been much less successful. Damar varnish and turpentine was much used in the final work. When drops are to be counted by the method given below, the oil film must be practically solid; otherwise the capillary forces produce an immediate and often startling redistribution of the precipitated granules, though they but seldom coalesce.

3. *Behavior of the precipitated droplets.*—In case of a petroleum film on the plate, the water droplets were sometimes seen to fall and float on the film, which is positive evidence against spurious droplets. They are usually black and circular in outline, but when the light is intense and axial, they are bright. Fixed globules are apt to be larger and more irregular. Particles may sometimes be seen to coalesce on collision, but this is rare.

On tipping the microscope so that the light does not penetrate the vividly colored drops axially, they seem to cast shadows in opposed directions for symmetrical inclinations on both sides; but in view of the aplanatic properties of spheres, the phenomenon is probably a case of refraction, with the shadow beginning at the edge of a caustic. Similarly, on moving the lamp horizontally to either side from the position corresponding to axial illumination, the globules become opaque, and look like round shining steel beads. The diameter of the beads has but little effect. If the lamp is moved until the field is dark, the plate looks like the starry heavens. These stars seem to be above the drops.



FIGURES 4, 5, 6.—DIAGRAMS SHOWING THE BEHAVIOR OF FOG PARTICLES.

After remaining in the plate for some minutes the fixed droplets often become rosette-shaped (apparently), at first showing a mere black spot in the center of the color disc, which gradually enlarges to a ring-shaped appearance *slowly moving radially outwards*. As a rule, the color[1] is eventually the same on the inside and the outside of the enlarged ring, the ring itself appearing red with black demarcations in the surrounding green field, as shown in the figure. On influx of air the structure becomes washed. This ring-shape may be merely apparent, but the small globules when at first deposited never show the same color within and without, the former being uniformly red and the latter white.

[1] The colors observed were afterwards found to be due to chromatic aberration of the microscope.

As the rings are not easily produced with a very viscous oil, it is probable that the droplet has here penetrated to the glass and that the oil film is drawn over it by the capillary forces at the common edge of the three media.

4. *Preliminary data.*—Before adopting the eccentric focussing device, many experiments were made to ascertain the cause of the uncertainty in catching the drops on the plate when kept in place, seeing that sometimes the precipitation was abundant, while at other times under the same apparent conditions drops did not fall. Failures occurred both for high and for low nucleation. From the outset it was improbable that radiation from the outside could affect the result. It was eventually ascertained that on tipping the condensation chamber after the fog had formed, so that the subsidence would reach the plate obliquely, a precipitate would usually appear. Again, an oblique current within the chamber and passing across the plate usually produced a deposit. Hence the drops actually exist within the fog, and success in bringing them down upon the plate is probably conditioned by very close isothermal adjustment of the plate to its surroundings, added to the advantages gained from incidental and favorable air currents. Hence a little time must always elapse before the drops persist at the plate, and hence the droplets from a shallow capsule do not appear. Using a film of mica as a plate the result was the same, and it is useless to attempt to enumerate the drops by this method. Those which fall are carried in by grazing air currents, while no drops are obtained from the fiducial space under the objective.

Nevertheless, the measurement of the diameters, d, of the drops obtained by the above method without modification is an excellent test of the results obtained elsewhere by computation. The factor of the ocular micrometer described above was .002 cm. per turn of the screw, or .00004 cm. per scale part of the drum divided into 50. The extent of plate covered by the breadth of the spider lines was about .0003 cm. The finest particles are of about this diameter, so that such measurements must at best be much inferior to photography with a scale attachment. The results are given in the following table, in which only those results among many are inserted for which the observations were clear and satisfactory. The coronal color with its diameter, s (chord of a radius of 30 cm.), are as observed when the eye and the source of light (Welsbach mantle seen through a small circular hole) were at distances 85 cm. and 250 cm., respectively, from the center of the condensation chamber. The exhaustion was usually to a pressure difference of 17 cm., but this is of no significance when diameters are alone to be observed. The particles were collected by tipping the chamber, sometimes in large numbers, but at other times sparsely distributed without apparent cause. Nuclei were conveniently obtained from burning charcoal. Both floating and fixed globules were examined with strong microscopic illumination. It was difficult to retain a clear image without frequently removing the plate, as the adjustment for focussing the plate within the chamber had not yet been adopted. A table showing the results from coronal measurements under the same circumstances is added.

TABLE 1.—DIAMETERS OF CLOUD PARTICLES. PRELIMINARY RESULTS, FIXED PLATE.

s	Corona.	Computed *d*.	Measured *d*.	Remarks.
cm		cm.	cm	
6.5	w b p	.00046	.00060	Fixed
6.5	w|b p	46	084	"
—	olive	32	050	Floating
—	olive	32	040	Fixed
6.4	g′|b|p	46	084	"
9.1	w r bg	37	052	Floating.
3.6	corona	82	096	Fixed.
3.8	"	76	116	"
5.8	w c g′	50	088	"
4.8	corona	60	088	"
2.4	"	120	222	"

TABLE 2.—DIAMETERS OF CLOUD PARTICLES. PLATE ADJUSTABLE.

	s	Corona	Computed *d*	Measured *d*
	cm.		cm.	cm.
Phosphorus	—	olive	.00030	.00042
nuclei.	10.0	w o bg	35	041
	8.2	w c g	39	060
	7.0	w p b g	44	050
	5.6	w r g	52	060
	3.3	corona	90	117

Floating globules were often observed in the act of coalescing; but this is much rarer than the passage of a floating droplet over a fixed one without interference. A distinct central bright area shading off into darkness was seen even in the floating globules when axially illuminated by intense light. The larger drops were often metallically green. The colors vanish after long standing, and they are particularly vivid immediately after falling. It was not even now possible, in spite of all precautions in tipping the vessel, to obtain an abundant crop of drops at pleasure.

The results are given graphically on the chart, figure 7, in comparison with the computed data of my earlier experiments (upper curve) as well as with my later experiments (lower curve). The observed results lie below the former where adiabatic conditions were assumed, and above the more recent experiments where the effect of the successive expansions was computed isothermally In other words, the observed diameters are intermediate, but nearer the older results. I will pass over these preliminary data, as they are probably too high because of the difficulty in focussing among others, to resume the subject in connection with the results obtained under much more favorable conditions below.

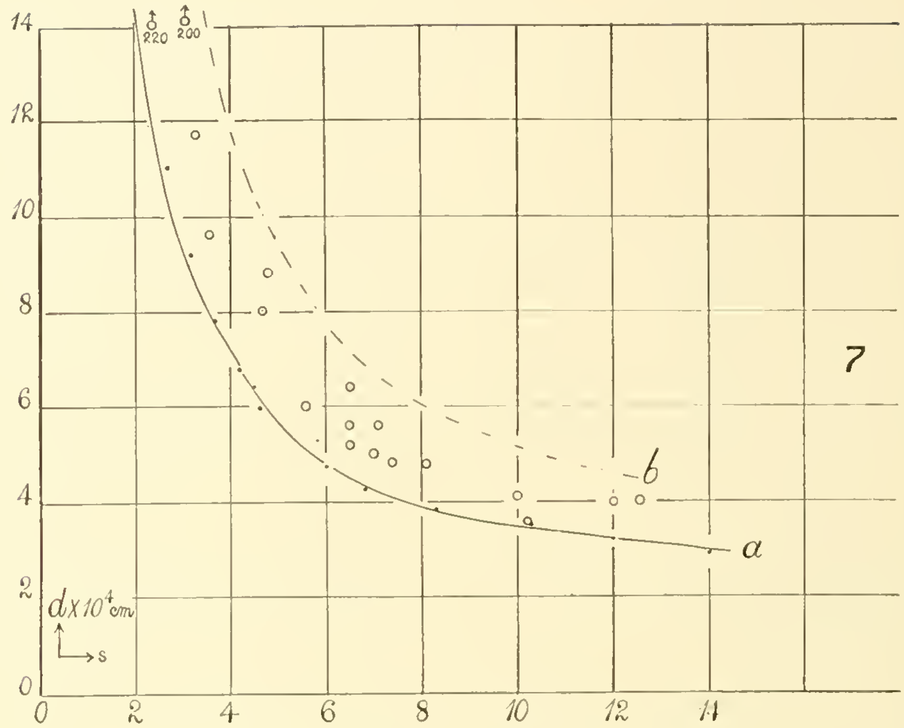


FIGURE 7.—CHART GIVING d IN TERMS OF s.

Improved Method.

5. *Number of droplets.*—The following results were obtained with the definite form of apparatus shown in figure 1. A method of estimating the nucleation from a direct count made under the microscope is obtained as follows: Let the plate be so rotated eccentrically as to catch the descending fog particles for a definite interval of time, t. If v be their velocity of subsidence, all particles within a height, h, will be caught, if

$$h = vt \qquad (1)$$

and

$$v = 10^6 d^2/3.24 \qquad (2)$$

where the usual value of the viscosity of air has been inserted. Furthermore, m grams are precipitated per cub. cm. by the given exhaustion, and if n be the nucleation

$$n = 6m/\pi d^3. \qquad (3)$$

Finally, if c is the area of the field seen in the microscope and n' the number of particles falling into this field

$$n' = nhc. \qquad (4)$$

From these equations n is obtained by eliminating v as

$$\sqrt[3]{n} = \frac{2.11 \times n'}{tcm^{2/3}10^6}.$$

The values of the constants usually adopted were $t = 30$ sec., $c = 144 \times 10^{-6}$ sq. cm., $m^{2/3} = 2.8 \times 10^{-4}$, whence $\sqrt[3]{n} = 1.75 \times n'$. The experiments to test this method often gave serviceable results, some of which are inserted in the following tables; but at times the n-values are out of proportion. The reason of this is threefold: In the first place n is found from $n^{1/3}$ with the usual difficulty. Again, in a simple arrangement like the above, air currents cannot be quite excluded. They may arise incidentally in the apparatus or the motion of the plate even if parallel to itself may stir the air unless some form of guard ring attachment is added. Particles are thus swept down upon the disc before and after the exposure, as was actually observed. The difficulty may be removed by adding a capsule above the plate or simply by decreasing the distance between the shield and the plate to a millimeter or less. Finally, if the oil film is semi-fluid and not quite fixed, if there is slight creeping, as was usually the case, the particles are redistributed after falling along stream lines where they cohere in strings and bunches, but without coalescing. This was also observed, and in fact the capillary forces involved are apt to be strong enough to counteract viscosity.

I have not thus far spent much time in correcting these defects, chiefly because the new results for the diameters of fog particles are more immediately interesting. The data are given in table 3.

TABLE 3.—OBSERVED DIAMETERS AND NUMBERS (per cub. cm.) OF CLOUD PARTICLES. $m = 4.7 \times 10^{-6}$g per cub. cm.; If $c = 144 \times 10^{-6}$ sq. cm., and $t = 30$ sec.; $\sqrt[3]{n} = 1.75\, n'$. Generally $\sqrt[3]{n} = 2.11\, n'/tc\, m^{1/3}\, 10^6$. Micrometer factor, .00004 cm.

	s	Corona.	$c \times 10^6$	t	n'	Observed n	Computed n	Observed d	Computed d
	cm.		cm.²	sec.				cm.	cm
	—	olive	140	30	37	271000	250000	—	—
	6.0	w r g	140	30	27	105000	90000	—	—
Phosphorus nuclei.	10.2	w o bg′	70	30	17	210000	210000	.00036	.00036
	7.4	w p b g	70	15	6	—	—	48	41
	7.1	w′ b p	—		—	—	—	56	.42
	4.7	corona	—		—	—	—	80	61

Particles as small as .0003 cm. present throughout.

	s	Corona.	$c \times 10^6$	t	n'	Observed n	Computed n	Observed d	Computed d
Phosphorus nuclei.	6.5	g b p	140	15	10	43000	100000	.00064	.00046
	6.5	g′ b p	—		—	—	—	56	46
	6.1	w r | g	—		—	—	—	72	48

Particles as small as .0003 cm. always present.

	s	Corona.	$c \times 10^6$	t	n'	Observed n	Computed n	Observed d	Computed d
Air nuclei.	4.5	cor	140	15	9	30000	40000	.00064	.00064
	6.5	g′ b p	—	—	—	—	—	52	46
	8.1	w c bg′	70	15	14	120000	150000	48	39
	8.2	w c bg′	70	15	16	180000	150000	—	39

Particles graded as usual.

6. *Diameters of fog particles.*—If the diameters measured are plotted in a chart together with the results computed from successive exhaustions in the older and in the more recent experiments, the present values again lie between the two curves, but now much nearer the lower (recent) curve than before. I shall not pause to interpret the differences which remain, but only to remark that the capillary forces at the area of contact of the droplet even with the liquid oil film may transform it to an oblate spheroid, and that diffraction at the circular edges of the drops is not excluded. If the nucleation, n_0, obtained from successive isothermal exhaustions and subsidence measurement, be accepted as correct (lower curve), the ratios of the nucleation found from the different methods tested will then be

From subsidence, $a = .0029$;	$d/d_0 = 1.0$	$n/n_0 = 1.0$
From lycopodium ($d = .003$ cm.), $a = .0034$;	" $= 1.2$	" $= .61$
From diffraction (blue), $a = .0034$;	" $= 1.2$	" $= .61$
From micrometer measurement, $a = .0037$;	" $= 1.3$	" $= .48$
Old results (adiabatic conditions assumed),	" $= 1.6$	" $= .24$

Since n is obtained from the cube of d, large differences of this kind are as yet inevitable, particularly as the particles measured in these different cases are not the same.

7. *Sizes of particles graded.* The point of particular interest which comes out on using the eccentric plate to catch the subsidence during 15 or 30 seconds, and at once examining the deposit, is the result that particles of all sizes are present. By far the greater number, however, have the maximum diameter. These particles are caught from the fog without interference, and it is not probable that coalescence or evaporation have been appreciably operative, so long as the corona remains the same throughout the micrometer measurement. The probable explanation is this: while the pressure decrement is growing from zero to the maximum δp, condensation is taking place on the greater number of particles throughout the whole of this interval. In other words, although the nuclei are graded in size, the greater number exceed a certain dimension and require almost no pressure decrement to induce condensation. These are the particles (diameter exceeding a certain inferior limit) which give character to the persistent corona. A minority of the graded particles are below the dimension in question, and upon these condensation does not take place until the higher values of the pressure difference are reached; some may even require the full decrement, δp. Thus it is that in the deposit of fog particles, one finds those of diameter .001 cm. intermixed with others of smaller diameter, even as far as .0002 cm. or less, all shining like beads. When fresh phosphorus nuclei are first introduced into the condensation chamber the result is a gray fog, but a relatively small white reddish corona is nevertheless discernible. Accordingly, the crop of droplets seen under the microscope contains not only surprisingly small but also relatively large droplets, with all intermediate diameters. Hence the indefinite fog and the small corona. The large olive (g b p) corona and

other of the early coronas are very apt to fade into a coarse white reddish corona. This is the evaporation of the smaller particles into the larger, which accounts, moreover, for the loss of nuclei during the first precipitation, to be caught in subsequent exhaustions. The successive coronas in a series gradually become sharper and the larger particles more uniform, but extremely fine particles are still present even when one approaches the normal coronas. The fine particles, however, belong to coronas so large and diffuse that their coronal effect scarcely modifies the strong coronas of the large particles even before the former vanish by evaporation.

When I first observed these different sizes of drops caught on a single plate, it seemed not improbable that a difference of the condensational effect of the negative and the positive ions might here be actually in evidence; but as all intermediate sizes are present at the outset, and particularly as large and small droplets still appear together long after all electrification has certainly vanished, this conclusion is not warranted. What continually favors uniformity is subsidence of fog. As the phosphorus nuclei are graded, it is probable that the very fine droplets are due to the initial or primitive nuclei from which the larger nuclei have grown by coalescence; or the fine droplets may be due to air nuclei associated with the phosphorus nuclei. All this will appear in the more minute photographic study of the subject detailed in the next section, and it will be further interesting to decide whether the nuclei generated by the X-rays are not also graded below a certain usually much smaller maximum diameter. That this maximum diameter will increase with the lapse of time allowed for coherence may be inferred.

The coarse and washed type of coronas obtained with nuclei produced by the X-rays is evidence of graded size, while the fog particles, so far as I have yet caught them, are of varied dimensions. In these cases the X-rays reached the inside of the condensation chamber through its waxed wood walls lined with wet cloth. To obtain a fairly strong and large corona an exposure to the rays lasting 5 to 10 minutes was needed, as the radiation was not very intense. In this interval the original extremely small nuclei are probably undergoing continuous growth, for instance, by cohering, so that on exhaustion particles of all sizes are revealed. In addition to the ragged coronas there is copious rain. Under these circumstances it seems reasonable that the time loss of nuclei must at the outset be proportional to the square but finally to the first power of the number, assuming that eventually the large nuclei do most of the catching.

II. MICRO-PHOTOGRAPHY OF FOG PARTICLES.

8. *Preliminary.*—In the preceding section [1] I described a series of experiments in which the diameters of fog particles were microscopically measured, directly. In the present section these particles are micro-photographed, and the negatives subsequently measured. The results, though interesting as a whole,

[1] See also *American Journ.* (4), XVII, p. 160, 1904.

are not as immediately available for quantitative discussion as was hoped. The number of nuclei per cubic centimeter and the diameters of the fog particles are respectively below and above the computed nucleation (Chap. VI), and the globules photographed are rarely of the same size for a given corona.

Very curious results, apparently capillary in character, were obtained, showing permanent pitting effects of the subsidence of fog on a film of viscous oil and persistent motion of globules in liquid oil.

9. *Apparatus and method.*—The apparatus needed is a modification of that described in § 2 of this chapter for the micrometry of fog particles, with the addition of a camera above the microscope. The usual form of camera attached to a substantial eccentric axis so as easily to be rotated into place or removed therefrom for inspection is satisfactory. The revoluble condensation chamber must be clamped in place. The camera may be focussed by the stage focussing screw of the microscope, so that a lens is apparently not necessary in the camera; but it is essential that the magnified fog particles be seen very clearly with the eye at the microscope, before photographing them, and this procedure is therefore not quick enough. It was thus found necessary to add a good lens to the camera adjusted for parallel rays and to adapt the eye for the same infinite focus by concave glasses. In this case, when the particles had been caught and put in place under the objective by the eccentric stage device described above (§ 2), the camera could be at once swung into position for photography. The endeavor to adapt a small kodak for the work was not very successful.

Magnification may be secured either at the objective, or at the ocular. Some space between the objective and the plate is desirable for safe manipulation, and therefore a half-inch objective will serve the present purposes better than a quarter-inch lens. The illumination must be axial to avoid astigmatism, but the use of condensers has not as yet been tried, and would probably promote evaporation of the fog particles. In general, reasonably small magnification, much light, and rapid photography are best conducive to success. In this way the time of exposure was gradually reduced from 20 seconds to 2 seconds or less. The positive ocular seen in the plates was used merely in the absence of a suitable negative ocular, inasmuch as the former was provided with a filar ocular micrometer. But a negative ocular containing a plate ruled in square millimeters would be far preferable.

The plate in these experiments was covered with an even coating of Damar varnish, neither too moist nor too dry. A clean microscope cover-plate of glass is dipped in the varnish, and the excess removed by placing it on edge. The film, which must be smooth, clear, and even, will be ready for use in a few hours. If too dry it should be soaked in turpentine, otherwise the particles adhere broadly to the plate and rapidly evaporate. If the plate is too moist, the particles float and cannot be photographed. No precise rules can be given. Naturally, the conditions surrounding the plate should be as nearly as possible isothermal, which implies a capacious air chamber for condensation.

10. *Incidental phenomena. Pitting.*—A curious phenomenon sometimes

accompanies the deposition of the fog particles on the film of viscous varnish, inasmuch as they leave a permanent impression. In other words, the plate becomes more or less permanently pitted after the fog particles are gone, appearing washed or dull to the naked eye, and not regaining the clear state until after the lapse of 12 hours or more. The effect occurs only in the case of fog deposition and is never present on the plate in the absence of a precipitate of fog. Hence it cannot be an air bubble effect.

The cause is probably to be associated with surface tension since the weight of the particle is negligible. If the particles were to break through and reach the bottom of the film of varnish, there is no obvious reason why the pitting should vanish like a viscous phenomenon in the course of time.

It is conceivable (Fig. 8) that the surface tension of the varnish is locally lessened by slight admixture, or at least the proximity of water, and that an alveolar structure of the surface is the result. In certain slides (No. 22) the presence of these "craters," as they may be called, seems to be clear in the photograph. At other times droplets shrinking in their cavity by evaporation were actually observed. But the phenomenon is rare and observation therefore uncertain.

11. *Dew.*—When the plate is dry, the beginnings of the formation of dew on its surface are apparent after long exposure. The dew particles are very fine even as compared with fog particles, the former as observed lying within .0001 centim. Their number is enormous, aggregating to fully 2 million or more per square centim. of the surface (slide No. 27). They do not further seem to interfere with the deposition of fog particles than by promoting adhesion, but this is naturally objectionable.

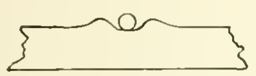


FIGURE 8.—DIAGRAM OF "CRATER."

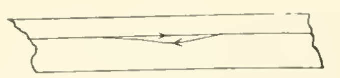


FIGURE 9.—DIAGRAM SHOWING CIRCULATION.

12. *Evaporation.*—The droplets, originally sharp in outline, become vague and washed on evaporation, doubtless because their curvature decreases, while the area of adhesion remains the same, to the detriment of the nearly spherical curvature at the beginning. Floating globules are usually much more uniform in size and remain more uniform, because the differences due to adhesion are absent (see §§ 9,13). It has been stated that when there is evaporation the photograph fails and a blank plate results. It may be assumed that a successful photograph implies as little evaporation of fog particle before the taking of the picture as during this interval.

13. *Floating and moving globules.*—A final very interesting phenomenon is met with in the case of fog particles floating in a liquid film of oil. It frequently happens under these circumstances that there is a sharp line of demarkation in the field of the microscope, probably an edge of contact of the semi-fluid matter on the plate. In all such cases there is apt to be continuous

motion of the submerged or partially submerged fog particles, to and from the edge on one side. They approach and leave in great armies, at first, gradually dwindling in number as they pass out of the field of view, eventually to be lost by evaporation. Sometimes both advancing and retreating fog particles are in sharp focus at once. At other times the advancing set is obviously above or below the other, to the extent of one or more tenths of a millimeter. Cases also occur in which there are two edges or a sort of geographical strait in the field of view, in which case particles are frequently seen moving from edge to edge until they vanish in number, probably from evaporation. Vortical or involved orbits of fog particles also occur.

In explanation of these phenomena it is necessary to bear in mind that the edge of retrogression mentioned is always nearly fixed, under the microscope. Hence it is not probable that that motion of the mixed oil (varnish-turpentine) due to concentration on evaporation can be the cause; for in this case the liquid would visibly gather itself up into a drop showing a shifting edge in the field. The possible motion of a liquid on its surface skin or similar capillary phenomenon is equally hard to reconcile with the stationary edge. The most probable explanation, it seems to me, is given by the annexed diagram, figure 9. If the film on the plate of glass is microscopically uneven and slightly inclined, the motion of a relatively liquid layer over a fixed layer may enclose a shallow region of liquid, in which eddying is kept up, as shown in the diagram, remembering, of course, that all motion is observed under the microscope. The particles indicate the motion of the skin circulation.

14. *Graded particles.*—Suggestion may finally be made as to the cause of the observed gradation of particles, where such gradation appears simultaneously with clear-cut coronas. In case of the X-rays the coronas are vague and washed, accompanied with copious rain. What is seen is a coarse red-rimmed fog. Here gradation is obviously due to the corresponding gradation in the sizes of the nuclei, as explained above. Something similar shows itself in the initial phosphorus or sulphur fogs.

The grading in question cannot be due to coalescence, not only because such coalescence is but very rarely observed, but because the volume increase is as the third power of the diameter. Sizes as 1 to 3 being very common, this would mean an equally frequent coalescence of 27 droplets, which could not escape detection. Moreover, the coronas in air retain a nearly fixed diameter until they are lost by subsidence.

Some difference of size must be due to a difference of surface adhesion; but if the oil stratum is of the same character throughout, this is not liable to be large without being detected in the picture.

The final cause for gradation, apart from original differences of nuclei, is evaporation. The occurrence of marked evaporation is at times beyond question, and it is then impossible, or nearly so, to obtain a photograph. In general, however, evaporation is obscure, and one may argue, as already suggested, that in the time (about 60 seconds) needed for adjustment and photography, the evaporation should be no less than during the anterior 15 or 30 seconds of subsidence during which the fog particles were caught. This would seem to be especially true where the particles persist for several minutes after photography, as is usually the case. Nevertheless, it is not impossible that the first precipitate prepares the plate (by evaporating partially) for the subsequent precipitation. The subject will be resumed in connection with definite results below.

Results.

15. *Photographic plates.*—Unfortunately, it is impossible to reproduce the photographic negatives obtained, except in certain cases; for not only are the fog particles frequently too small, but slides suitable for the measurement of number are indistinct in relation to diameter. To obtain a plate in which the particles actually stand out is naturally a matter of chance, as this will depend on many conditions (light, evaporation, focus, etc.) beyond the observer's control in expeditious work. Curiously enough, the plates obtained for fog particles condensed on the persistent nuclei produced by the X-rays in dust-free air are the best of my series, and are therefore reproduced.

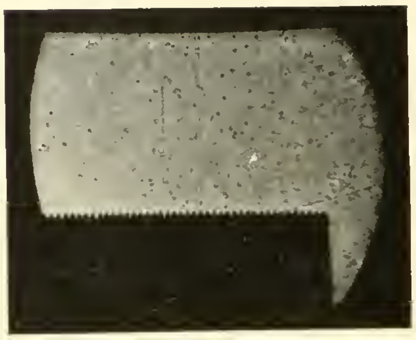
To measure the sizes of the particles on the plates a filar micrometer of low power was used. To count them, the slide was divided off into fields of convenient size, and the number then enumerated under a lens, taking all the fields in clear focus in succession.

16. *Tabulated results.*—The following tables show the general results for about 50 photo-micrographs. The kind of nuclei used are given in the first column, the coronas and their angular diameters ($s/30$, nearly) in the second and third. The mean diameter, d, of fog particle measured from the photograph and the limits of d observed, follow. The next two columns show the number of nuclei, n, obtained from the photograph by the equation of this chapter, § 5, and the observed limits of n for the different fields counted. The last columns are explanatory and usually show the film of oil or varnish used to catch the precipitate and the character of the plate.

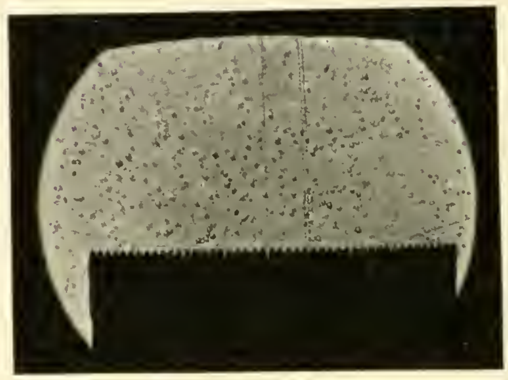
17. *Remarks on the tables.*—The use of rough oil films (tallow, paraffine, wax, etc.) is naturally unsatisfactory, but the particles are easily recognized (No. 3). Plates Nos. 4, 6, 22, though very perfect as photographs (large camera magnification) showed a permanent impression which lasted 6–12 hours, as already stated. In No. 8 only a few particles were caught. Nos. 9 and 10 were taken with a $\frac{1}{4}$-inch objective, and though good in themselves were hard to obtain, and showed the advisability of the weaker objective ($\frac{1}{2}$-inch), favorable to shorter times of exposure. No. 11, and particularly No. 22, gave evidence of the occurrence of "craters" (Fig. 8) in the varnish film left after the evaporation of the fog globule. As a whole, the photographs on the X-ray nuclei are the most successful, and in No. 23 in particular the particles stand out on the photograph. In No. 31 particles were deposited on the plate during the vortical motion occurring on influx of air while in No. 32 the motion of the particles (film too liquid) shows streaks on the plate.

No. 30.—X-ray nuclei. Scale part, .0030 cm. Fall 45 sec.

No. 27.—X-r nuclei. Sc part, .0030 c Fall 15 sec. D in negative.



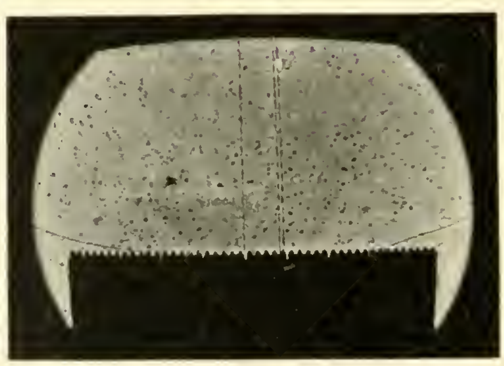
No. 10.—Air nuclei. Scale part, .0012 cm. Fall 30 sec.



No. 23.—X- nuclei. Scal part, .0030 c Fall 30 sec.

No. 25.—X-ray nuclei. Scale part, .0030 cm. Fall 30 sec.

No. 9.—P nuc Scale part, . cm. Fall 4 sec.



No. 22.—Scale part, .0030 cm. "Craters." Fall 30 sec. X-ray nuclei.

No. 4.—P nuclei. Scale part, .0044 cm. Fall 20 sec.

Figure 10.—Micro-photographs of Fog Particles, Precipitated on Persistent Nuclei usually Produced by the X-rays in Dust-free Air.

TABLE 4.—FIRST SERIES OF NEGATIVES MEASURED FOR d AND n. $m = 4.7 \times 10^{-6}$. $\sqrt[3]{n} = 2.11\ n'/tcm^2\ {}^3 10^6$. $t = 20^s$ to 30^s. $\delta p = 17$ cm.

Nuclei.	t	No.	Corona.	s	$d \times 10^5$	Limits of $d \times 10^4$.	From photograph $n \times 10^{-3}$.	Limits of $n \times 10^{-3}$.	From coronas $n \times 10^{-3}$.	Ratio.	Remarks.	Film
	Sec.			cm.	cm.	cm.						
P		2	Lycopod.		312							—
P		3	w c g′	8.9	55	4–7	—	—			Rough.	Tallow.
P	20?	4	w c g′	8.6	76	5–10	250	–7000	160	.6	Persistent.	Damar.
P	20	5	"olive"	>12	57	4–9	51	36–220	250	5.	Fine.	"
Air	30?	6	w c g′	8.4	69	3–10	33	–270	151	5.	Persistent.	"
Air (stale)	30	7	corona	5.6	109	10–13	18	–1500	56	3.	Good but injured.	
P	—	8	fine fog	—	50!	—	—	—	—	—	Evaporated.	
P	45	9	w p	7.3	90	5–14	75	–1400	130	1.7	Clear.	
	30?	10	corona	5.6	84	7–10	?250	175–2600	56	.2	Clear.	
	"	11	w c g′	7.6	—	—	—	—	—	—	Failed. Craters.	
P	30	12	w r′	>12	54	4–7	?4		—	—	Vague and faint.	
Air (stale)	"	13	corona	4.9	77	5–10	8	1–125	45	6.		
" "	"	14	"	4.6	96	7–11	7	–170	42	6.	Clear.	
" "	"	15	"	4.6	97	9–10	13	12–330	42	3.	Clear but not all focussed.	
P	"	16	y o g′	9.2	62	4–10	? 16	7–230	180	11.	Clear but dark.	
P	"	17	w c g′	8.3	82	5–12	61	3–1300	150	2.5	Good.	
P	"	18	g′ b p	6.5	62	3–10	6	–340	105	—	Evaporated.	
P	"	19	w c g′	8.3	55	3–11	34	2–970	150	4.4	Clear but uncertain.	

The results with fog particles condensed on nuclei of atmospheric air (table 6) and photographed by a small kodak were not very successful, due to secondary causes. In the small vessel used, the tendency to evaporation was accentuated, and the fog particles had in many instances evaporated before the photograph could be taken. Hence d was not measured.

In table 7 the chief purpose was a comparison of the precipitates obtained when using an ordinary stopcock to effect the exhaustion and on using the instantaneous valve described above.

Inferences.

18. *Precipitation per cubic centimeter.*—The precipitation, m, computed from the plates Nos. 4, 5, and 6, for instance, would be 57×10^{-6}, 4.8×10^{-6}, 5.7×10^{-6} grams per cubic centimeter, respectively. In the first case the deposit is excessive, probably due to eddy currents, in the second nearly correct, in the third too large. It is preferable, however, to compare the values of d and n obtained from the photographs directly with the data from coronas.

TABLE 5.—NUCLEI DUE TO X-RAYS OR TO FILTERED P EMANATION; DATA FOR d AND n. $m = 4.7 \times 10^{-6}$; $\sqrt[3]{n} = 2.11\, n'/tcm^{2/3}\, 10^6$; $t = 15^s$–45^s; $\delta p = 17$ cm.; FILM, SOFT DAMAR VARNISH.

Nuclei.	Fall.	No.	Corona.	s	$d \times 10^5$	Limits of $d \times 10^4$.	$n \times 10^{-3}$	From coronas $n \times 10^{-3}$.	Ratio.	Remarks.
	s.									
X-ray	30	20	w p′	6.9	101	6–11	—			Fogged plate.
"	30	21	w r′	5.7	100?	—	—			Do.
"	30	22	w p′	5.7	133	7–16	4.3	60	14	Pitted. Shows crater.
"	30	23	corona	2.8	129	10–20	1.3	8	6	Good.
"	30	24	wp′	5.3	—	—	—	—	—	Lost.
"	30	25	wp′	5.3	125	5–21	24.4	52	2.2	Good.
"	30	26	w r′	3.6	86	5–10	3.1	18	5.8	Too late.
"	15	27	w r′	3.1	130	7–22	4.1	11	2.7	Good. Shows dew.
"	15	28	w r′	4.4	105	8–15	19.7	36	1.8	
"	30	29	w r′	2.8	210	16–24	?.17	8	?47	Evaporated?
"	45	30	w r′	4.6	139	9–20	1.9	42	22	Good.
P	—	31	w r′	>12	65	5–10	—	—		On influx.
P	30	32	w y′	10.4	—	—	—	—		Streaks.
P (stale)	30	33	w p	5.5	65	5–7	27.0	55	2	
P	30	34	w br	4.5	86	7–12	4.9	40	8	Good.
P	30	35	w r′	>12	65	4–11	?13.8	250	18	Good (mixed small and large).
P	20	36	corona	2.6	140	6–20	5.8	7	1.2	Good.
P	30	37	wp	5.3	95	8–11	?13.8	50	3.6	Mixed small and large.
P (stale)	30	38	w r′	>12	39	2–6	? 3.1	250	—	Out of focus.
P	30	39	w c′ g	7.8	87	8–10	? .10	140	—	Out of focus.

TABLE 6.—AIR NUCLEI; DATA FOR n. $m = 4.7 \times 10^{-6}$g/cm³; $\sqrt[3]{n} = 2.11\, n'/tcm^{2/3}\, 10^6$; $t = 30^s$–15^s; $\delta p = 17$ cm.; $c = 5 \times 26 \times (.00304)^2$.

No.	Corona.	s	n'	t	From photograph $n \times 10^{-3}$.	From coronas $n \times 10^{-3}$.	Ratio.	Remarks.
40	y′ o g′	6.8	105	30	10.8	117	10	
41	w′ o g′	6.8	87	30	6.7	117	17	
42	w o g	6.8	Failed		—	117	—	Accident.
43	w br cor	4.8	102	30	7.4	45	6.1	Good.
44	w br cor	4.8	53	15	9.0	45	5.0	
45	w′|b|r′	4.6	54	15	12.3	42	3.4	Very good.
46	w r g	5.7	67	15	6.1	58	9.5	Vague.
47	w o g	6.8	Failed		—	—	—	
48	w r g	5.8	Failed		—	—	—	
49	g b p	6.4	75	15	31.3	100	3.3	Good.
50	g b p	6.4	105	15	85.8	100	1.2	Good.

19. *Diameters and numbers.*—The d-values given by the photographs are almost without exception larger than the corresponding diameters computed

TABLE 7.—MISCELLANEOUS EXPERIMENTS. ROOM AIR FROM FLOOR. LARGE VESSEL. $\sqrt[3]{\bar{n}}=6.23^{n'}_{t}$. EXHAUST THROUGH STOPCOCK.

No.	Corona.	s	n'	t	By photograph $n \times 10^{-3}$.	From coronas $n \times 10^{-3}$.	$\frac{n_{\text{cor}}}{n_{\text{obs}}}$
53	wp cor	7.3	144	30^s	26	127	4.9
54	w o g′	9.8	168	30	42	200	4.7
55	w ro g	8.8	147	30	28	170	6.1
56	w o g′	9.8	73	30	?3.4	200	? 59
							Mean, 5.2

EXHAUST THROUGH INSTANTANEOUS VALVE.

No.	Corona.	s	n'	t	By photograph $n \times 10^{-3}$.	From coronas $n \times 10^{-3}$.	$\frac{n_{\text{cor}}}{n_{\text{obs}}}$
57	w o g′	9.8	138	30^s	24	200	8.4
58	w o	4.6	92	30	7.2	42	5.8
59	w c g′	8.3	130	30	?19	135	71.
60	w r g′	8.9	—	30	—	—	—
61	w c g′	7.8	170	30	45	140	3.1
62	w c g′	7.9	126	30	18	145	8.1
							Mean, 6.3

from coronas. No doubt this is in part due to adhesion; but the chief reason is the occurrence of so many large particles with the small, so that the average value of d given by the photographs is within certain limits an arbitrary quantity, depending on the distribution of particles selected for measurement. If the values of d be plotted graphically in terms of s, they do not make a smooth curve, and these values are from 1.5 to 2 times larger than the coronal values of d. For this reason the measurement of d in the photographs was abandoned. The data are much inferior to the above micrometer measurements of floating globules.

The n-values in the photographs, being obtained independently and not conditioned by so perfect a reproduction of form, etc., as are imperative in measuring diameter, may be considered more trustworthy. Nevertheless, they also fail to suggest a smooth curve, though they are, as a whole, very much smaller than the coronal n-values. If observations obviously in error be omitted, the following are the mean values of the ratio n (coronal) to n (photographic) obtained from the successive tables. Only in two or three instances are these ratios less than one.

Table 4. Ratio = 4.1,
" 5. " = 3.8,
" 6. " = 4.4,
" 7. " = 5.9,

or on the average the coronal n-values are about $4\frac{1}{2}$ times as large as the n-values obtained from the photographs.

20. *Explanation of discrepancies.*—The reason for this result would at first sight be obviously given by the evaporation of the fog particles on the plate, before and during the photographic exposure. But as the d-values were from 1.5 to 2 times too large, it is necessary to guard against accepting this explanation too hastily: for inasmuch as the d-values and the n-values are independently given by the photograph, their relation must be

$$nd^3 = 6m/\pi.$$

Now it is rather curious that while the n-values are 4.5 times too small, the independent d^3-values should be 3 to 6 times too large. In other words, on using the average d- and the average n-values given by the photographs, an approximately correct value for m, the precipitation per cub. centim., follows, even though d and n are found quite independently. Add to this the fact that if evaporation occurs the photograph usually fails entirely. It is quite improbable that on the average a definite number, about 78 per cent., of the fog particles should incidentally evaporate.

Before proceeding further it will contribute to clearness if some of the better data of table 4 be summarized. The d-values show the marked occurrence of larger particles on the photograph, whereas the smallest particles more nearly correspond in size.

TABLE 8.—SUMMARY OF CERTAIN DATA FROM TABLE 4.

No.	Nuclei.	Time of subsidence	s	Corona.	Diameter from photograph $d \times 10^4$.	Diameter from coronas $d \times 10^4$.	Number from photograph $n \times 10^{-3}$.	Number from coronas $n \times 10^{-3}$.
		sec.	cm.		cm.	cm.		
4	P	20	8.6	w c g′	5–10	3.8	?250	160
5	P	20	>12	olive	4–9	3.2	51	2.50
6	Air	30	8.4	w c g′	3–10	3.8	33	160
9	P	45	7.3	wp	5–14	4.1	75	130
10	P	30	5.6	cor	7–10	5.2	?250	60
23	X-ray	30	2.8	cor	5–20	10.6	1.3	8
25	"	30	5.3	w r′	5–21	5.5	24	50
27	"	15	3.1	"	7–22	7.5	4	11
30	"	30	4.6	"	9–20	6.2	2	42

If the micrometer data (§§4–6) be used for the d-values, the ratios of coronal and measured diameters are

$s =$	4	6	8	10	12
Ratio =	1.3 to	1.2	1.2	1.2	1.2
	1.6	1.6	—	—	1.3

or the d^3-values are 1.7 to 4.1 times too large. Now in these instances the fog particles were often measured while floating, so that adhesion in these instances must have been a negligible factor. Nevertheless the d-values are not all incompatible with the n-values.

21. *Summary.*—The curious state of the case mentioned is not reassuring. Briefly, the photographic n-values and the photographic values for diameter, d, do not make an incompatible system, though both differ materially from the coronal values, the former (d) being larger, the (n) smaller. If one ascribes the large visible diameters to adhesion, and the small numbers counted to evaporation, the compatibility of the two sets of independent data (d and n) is not explained.

I have therefore concluded that the results in question suggest that the smaller particles evaporate rapidly into the larger. Hence while the mass of water precipitated per cubic centim. remains constant, the diameter of the fog particles soon increases while their number decreases (by evanescence of the smaller) in such a way that $n \times d^3$ remains very nearly constant throughout. In place of evaporation, capillary coalescence of the initial very minute droplets is an even greater probability; and such coalescence I have often seen under the microscope on observing dew droplets [1] very fine and close together. It is rather interesting that the evidence in favor of this complicated behavior is so strong.

That such evaporation occurs appreciably in the coronas is not probable, because in a good apparatus they retain their character during the whole of the subsidence. The plate of glass being slightly warmer contributes to the effect observed.

Hence neither the micrometric nor the photometric method can be relied upon for undistorted results. Whenever graded particles are present the evidence must be sought in the washed and blurred coronas. If the coronas are clear and multi-annular, the gradation observed under the microscope must be a secondary effect not present in the coronas themselves.

III. RESULTS FROM SUBSIDENCE.

22. *Object and method.*—The difficulties mentioned in the last sections induced me to look for corroborative data in the evidence obtainable from special experiments with subsiding fog particles. These are easily made in the apparatus for measuring atmospheric nucleation as described in Chapter VIII, Fig. 1. The observer, provided with a stop-watch, simply determines the time during which the straight horizontal line of fog descends a given distance, say 5 centimeters, from the top. In other cases there were two marks between which subsidence was noted.

23. *Results.*—In the experiments given in the following tables, the watch was started simultaneously with the exhaustion and stopped when the given fall of fog line had been reached. The equations are then successively

$$10^4 d = 18\sqrt{v}, \qquad ds = a, \qquad n = 9/(d^3 \times 10^6) = 1550/v^{3/2},$$

where n is the number of particles per cubic centim., d the diameter of each, v the rate of subsidence.

[1] If a microscope plate is dipped into thin, rapidly drying methyl alcohol varnish, a milky deposit of dew is often seen on the film when solidifying. This film behaves under the microscope as stated in the text.

TABLE 9.—VALUES OF a AND n. AIR NUCLEI. $n = 6m/\pi d^3 = 9/10^6 d^3$; $10^4 d = 18\sqrt{v}$; $ds = a$.

Corona.	s	$10^3 \times v$	$10^4 \times d$	a	$10^{-3} \times n$	Constant $10^3 \times v$
	cm.	cm./sec.	cm.			cm./sec.
w o | g	5.8	77	5.0	.0029	72	70
w r g	5.4	84	5.4	34	56	80
gy o	6.5	72	5.3	34	62	60
w ro g	6.2	89	5.5	34	53	65
w o g	6.2	89	5.5	34	53	65
w r g	5.9	85	5.4	32	56	70
g′ | b | p	4.5	180	7.6	34	20	123
Do.	4.5	116	6.1	28	39	123
Do.	4.5	130	6.5	29	33	125
w | b | p	4.6	122	6.3	29	36	115
w r g	5.9	107	5.9	35	44	70
w r g	5.7	102	5.7	33	48	75
g b p	4.6	128	6.4	30	34	115
y′ bg	6.2	77	5.3	33	59	65
w r g	6.2	79	5.4	33	59	65
g | b | p	4.6	156	7.1	33	25	115
w g | r	4.5	192	7.9	35	18	123
w r g	4.5	122	6.3	28	36	123
w r g	5.6	94	5.5	31	53	75
w r g	5.5	104	5.8	32	46	80
y′ o g	5.8	107	5.9	34	44	70
w r g	5.7	125	6.4	36	35	75
w c g	5.4	86	5.5	30	55	80
y o b′	6.2	76	5.3	33	60	65
g | b | p	4.8	140	6.7	32	29	105
g b p	6.0	72	5.3	32	60	65

$$\text{Mean } a \text{ in decades } \left.\begin{array}{r} .00322 \\ 304 \\ 327 \\ 320 \\ 329 \end{array}\right\} a = .00320$$

TABLE 10.—FURTHER RESULTS FOR SUBSIDENCE. $n = 6m/\pi d^3 = 9/10^6 d^3$; $10^4 d = 18\sqrt{v}$; $ds = a$.

Corona	$s_{19.5}$	$10^3 \times v$	$10^4 \times d$	s_{30}	a	n	Constant $10^3 \times v$
y br bg	4.2	79	5.1	6.5	.0033	68000	58
w o g	4.1	74	4.9	6.3	31	76000	62
w br cor	3.1	135	6.6	4.8	32	31000	105
w | b | p	2.9	114	6.1	4.5	27	40000	122
w y cor	3.0	125	6.4	4.6	29	34000	117
w | b | r	3.2	106	5.9	4.9	29	44000	100
w y cor	2.3	167	7.4	3.5	26	22000	215
w c g	2.7	143	6.8	4.1	28	28000	150
w br cor	2.2	200	8.1	3.4	28	17000	230
w o g	2.8	125	6.4	4.3	27	35000	135
w rg	2.7	140	6.7	4.2	28	30000	145

Corona.	$s_{19.5}$	$10^3 \times v$	$10^4 \times d$	s_{30}	a	n	Constant $10^3 \times v$
cor	2.2	157	7.1	3.4	24	25000	235
wp cor	3.3	94	5.5	5.1	28	54000	90
w|b|p	3.0	102	5.7	4.6	26	49000	117
cor	2.3	230	8.6	3.6	31	14000	210
cor	2.9	?109	5.9	4.5	27	44000	123
wbp	2.8	111	6.0	4.3	26	42000	135
w o g	2.8	135	6.6	4.3	28	24000	135
w|b|r	3.0	98	5.6	4.6	26	51000	117
g b p	3.0	102	5.7	4.6	26	49000	117
w r g	3.8	81	5.1	5.9	30	68000	68
g b p	3.0	105	5.8	4.6	27	45000	117
w r g	2.9	115	6.1	4.5	27	39000	123
wp cor	3.4	91	5.4	5.2	28	57000	90
wog	3.0	122	6.3	4.6	29	36000	117
w rg	2.8	140	6.7	4.3	29	30000	135
w o g	2.8	109	5.9	4.4	26	44000	130
g b p	2.9	122	6.3	4.5	28	36000	123
g|b|p	3.1	105	5.8	4.8	28	46000	105
wp cor	3.1	100	5.7	4.8	28	48000	100
g b p	4.1	68	4.7	6.3	30	86000	62
g b p	2.9	100	5.7	4.5	26	48000	123
w br cor	3.0	100	5.7	4.6	26	48000	117
w br r	2.9	105	5.8	4.5	26	46000	123
w o cor	2.9	120	6.2	4.5	28	38000	123
w o g	2.8	140	6.7	4.3	29	30000	135
w rg	2.8	143	6.8	4.3	29	28700	135
wp cor	3.0	111	6.0	4.6	28	41000	117
w rg	2.9	143	6.8	4.5	31	28700	123
g b r	3.0	109	5.9	4.7	28	44000	110
w br cor	3.0	128	6.4	4.7	30	34000	110
g b p	4.0	60	4.4	6.2	27	106000	64
g p b	4.2	64	4.5	6.5	29	99000	58
g b p	4.0	69	4.7	6.2	29	87000	64
w rg	4.0	85	5.3	6.2	33	60000	64
w y g	4.2	79	5.1	6.5	33	68000	58
w y cor	2.9	128	6.4	4.5	29	34000	123
w o cor	2.9	152	7.0	4.5	31	26000	123
w ro g	4.0	76	5.0	6.2	31	72000	64
w p cor	3.2	98	5.6	4.9	27	51000	100
w br cor	3.0	120	6.2	4.6	29	38000	117
cor	2.9	120	6.2	4.5	28	38000	120
w p cor	3.3	91	5.4	5.2	28	57000	88
w b p	3.0	96	5.6	4.6	26	51000	117
w rg	2.9	132	6.5	4.5	29	32000	123
w r g	2.7	140	6.7	4.2	28	30000	135
w p cor	3.3	98	5.6	5.1	29	51000	90
w r g	2.9	132	6.5	4.5	29	32000	123
cor	3.0	116	6.1	4.6	28	40000	117
wp cor	3.6	91	5.4	5.5	30	57000	80
w r g	4.0	78	5.0	6.2	31	72000	65
g b p	3.0	105	5.8	4.6	27	46000	117
wg cor	1.8	215	8.3	2.8	24	15800	330
wr cor	2.0	200	8.0	3.1	25	17300	280
wr cor	2.0	200	8.0	3.1	25	17300	280
cor	1.9	210	8.2	2.9	24	16400	320
cor	2.4	156	7.1	3.7	26	25000	195
cor	2.1	205	8.2	3.2	26	16700	265

24. *Remarks on the tables.*—Constructed graphically, the results of table 9 are irregularly below the coronal results. The results of table 10 are somewhat smoother and in the main agree with the coronal data. Thus for the green coronas (see Chapter VI, § 29, table 17)

coronal datum, g b p, $n=96{,}000$,
from table 10, g b p, $n=106{,}000$, 99,000, 87,000, 86,000; mean, $n=95{,}000$.

or the mean values are about the same. In case of low nucleations and small coronas the subsidence results are much too high as compared with the coronal results, implying too small a value of the v of subsidence.

The only explanation which suggests itself for this unexpected behavior is the occurrence of acceleration in the motion of the fog particles. Accordingly the following experiments with very small coronas (large particles) were tried as a test.

Normal corona with $s = 2.9$.

Fall, $f = 2$ cm.	time = 15	15	13	16	16
4	25	21	24	25	28
6	32	27	30	30	—

Thus $\sqrt{f} = 1.0$	Mean $t = 15$	Ratio = 15
1.4	25	17
1.7	30	18

indicating that the uniformly varied motion is only very gradually retarded by the air resistance encountered. The following table contains similar data for larger coronas, in none of which the evidence of acceleration is absent.

TABLE 11.—MEAN RATES FOR SUCCESSIVE DISTANCES OF 2 cm. EACH.

Corona.	s_{30}	Time for successive falls of 2 cm each. t sec.	t sec.	t sec.
w rg	5.7	18	23	22
w|b|p	4.6	20	18	16
w ro g	4.6	20	15	12
w r g	4.4	17	12	10
wp cor	3.4	13	8	5
w br cor	4.6	—	—	—
w b p	4.7	19	14	—
w r g	4.7	20	14	12
w r g	4.5	15	14	11
w b p	4.6	23	15	17
cor	1.9	13	8	6

These results rob the subsidence method of much of its trustworthiness except when the particles are very small, when other difficulties step in: for large coronas are not persistent in character.

The case may be stated by computation as follows: The velocity at which force is annulled by the resistance is

$$v = (10^4 d/18)^2 = .31 d^2 \times 10^6$$

from which the following table has been computed.

TABLE 12.

s = 1.5 cm.	d = .00180 cm.	v = 1.00 cm./sec.
2	143	.63
3	098	.29
4	072	.161
5	055	.093
6	047	.068
7	042	.053

If the results of this table are laid off graphically in a chart, the column marked "constant $10^3 \times v$" in tables 9 and 10 above may be obtained from it. It will then be seen that in most of the instances of small coronas in table 10, the observed velocity is less than the limiting velocity. Hence these data are to be rejected, and it follows that the subsidence method is scarcely applicable until the middle g-b-p corona ($s = 6.2$–6.5) has been reached. The mean value of a computed from the admissible data of table 10 is in successive decades, .00284, .00290, .00293, .00290, giving a mean value of $a = .00289$. This agrees closely with the datum (.0029) accepted in the above coronal tables, but is much below the value in table 9. Hence the following experiments were made with large coronas in the cubical apparatus.

25. *Further results.*—The data of the following table 13 were obtained by observing the time of fall for three successive distances, of 2 cm. each (usually), with three stop-watches. The results taken were those cases only where the three intervals observed are nearly the same. The fog was usually precipitated in the long vessel for observing atmospheric nucleation on air nuclei. If the fog line became billowy before the last observation was reached, this was discarded. The mean results are all given at a temperature of about 20° centigrade.

The new results like the above fail to suggest a smooth curve; though it would be difficult to obtain them under more generally trustworthy conditions than in this large vessel, showing a fog line half a meter long. The slightest variation of temperature, etc., gives rise to an undulatory fog line or produces a washed upper surface to the fog-bank. After a lapse of time of about 1 min. the demarcation is rarely available. In the very large coronas above g-b-p, the color and the character of the coronas is fleeting. In fact, a total change is liable to occur within a fall of one centimeter. Such results have no meaning.

If these data be compared graphically with the results of tables 1, 8, and 13, Chapter VI, they will be found to agree with them as well as these results agree with each other. In fact, the subsidence data fall very nearly on the curve corresponding to the fourth part of table 13.

TABLE 13.—DIAMETER AND NUMBER OF FOG PARTICLES FROM SUBSIDENCE MEASUREMENTS. $d \times 10^4 = 18\sqrt{v}$; $n = 9/d^3 \times 10^6$; $\delta p = 17$ cm.

Corona.	s	Mean $v \times 10^3$.	Mean $d \times 10^4$.	Mean $a \times 10^4$.	Mean $n \times 10^{-3}$.
	cm.	cm/sec.	cm.		per cm³.
w r g	5.8	86	5.3	31	62
w r g	5.9	82	5.2	30	66
w o g	6.2	74	4.9	30	76
w o bg	6.6	68	4.7	31	86
w o bg	6.8	69	4.7	32	85
w g b p	12.	34	3.3	—	250
g b p	6.3	62	4.5	28	99
g b p	6.3	62	4.5	28	100
yg br bg	6.6	66	4.6	31	91
w r g	5.9	80	5.1	30	68
w r g	5.7	81	5.1	29	66
y o bg	6.2	72	4.8	30	80
Do.	6.2	71	4.8	30	82
w c g	5.8	83	5.2	30	64
w p cor	5.2	97	5.6	29	51
w o bg	9.2	37	3.5	32	220
y o bg	11.6	31	3.2	37	280
w o bg	9.4	34	3.3	31	240
w o bg	9.4	34	3.3	31	240
w o bg	9.9	36	3.4	34	225
w c g′	8.0	43	3.7	30	170
w y o bg	6.2	74	4.9	30	76

The nucleation for the g b p corona (n = 100,000) agrees closely with the mean results above (n = 96,000), table 17.

Beyond the g b p corona (n = 100,000), however, the new data for n are with few exceptions much larger than the coronal values, at least with the interval s = 6 to 10 cm. From the difficulty encountered in observing this very slow subsidence and the variable coronas, the discrepancies are much more liable to rest with the subsidence data than with the other (coronal) group.

IV. SUMMARY OF RESULTS FOR NUCLEATION.

26. *Preparation of a table for deducing the nucleation from the observed coronal aperture.*—In conclusion, it will be useful to collect all the data obtained for the nucleation on a single sheet. Accordingly a chart was drawn up (too large for convenient reproduction here) containing the results of Chapter VI, table 1, series 1 and 2, table 8, series 1 and 2, and table 13, series 1, 2, and 4, as well as the best subsidence data of the last section. The latter are to be distinguished by a special symbol. The curves are found to lie closely together until the lower g b p corona (s = 4.3 4.5) is reached, where the first periodicity occurs. They then pass with wider divergence through the middle g b p corona

(s = 6–6.5), finally with still wider divergence to the upper g b p corona (s = 12). The nucleations corresponding to these double inflections are about as 1, 2, 3 (n = 4,000 to 5,000, 10,000, 300,000). The mean curve as far as the middle g b p corona is to be separately constructed with the ordinates (nucleations n, while the abscissas are apertures, s) enlarged 10 times. The lower periodicity must be ignored from the crowded condition of coronas here; the upper periodicity preferably presented as a discontinuity of the curve.

The graph so obtained was used for all the reductions of the nucleation of Chapter IX and elsewhere. From it table 14 was constructed. The nucleation n may finally be reduced to air at normal pressure and temperature.

TABLE 14.—FOR THE REDUCTION OF NUCLEATIONS (n nuclei per cub. cm. of the partially exhausted fog chamber). FROM APERTURES s AND S. PRESSURE DIFFERENCE, 17 cm. of Hg.

s, chord in cm., when the goniometer arms are 19.5 cm. long.
S, " " " " " " " " 30 " "

s.	S.	$n \times 10^{-3}$.	Corona.	s.	S.	$n \times 10^{-3}$.	Corona.
cm.	cm.			cm.	cm.		
1.0	1.5	1.5	normal	2.8	4.3	28	
1.1	1.7	1.7		2.9	4.5	31	
1.2	1.8	2.0		3.0	4.6	35	w r
1.3	2.0	2.5		3.1	4.8	38	
1.4	2.2	3.0		3.2	4.9	42	
1.5	2.3	4.0		3.3	5.1	45	g′ B p
1.6	2.5	5.0		3.4	5.2	49	
1.7	2.6	6.0		3.5	5.4	53	w P cor
1.8	2.8	7.0		3.6	5.5	57	
1.9	2.9	8.5		3.7	5.7	61	
2.0	3.1	10.0		3.8	5.8	66	w c
2.1	3.2	11.5		3.9	6.0	70	
2.2	3.4	13.5		4.0	6.2	75	w r
2.3	3.5	15.5		4.1	6.3	80	
2.4	3.7	17.5		4.2	6.5	85	
2.5	3.8	20	w c	4.4	6.8	95	ygb o g
2.6	4.0	22		4.2	6.5	100	g B p
2.7	4.2	25		4.5	6.9	120	w P cor

NOTE.—The photographs of §§15–21 were made from fog particles condensed (as stated) on *persistent* nuclei. No attempt was made to photograph the fog particles condensed on ions or fleeting nuclei, because the high exhaustions needed would have endangered the large condensation chamber. I shall therefore return to the subject elsewhere with a modification of apparatus and with this specific point in view.

CHAPTER VIII.

THE CORONAL METHOD OF ESTIMATING ATMOSPHERIC NUCLEATION.

1. *Introductory.*—To produce coronas the nuclei must be very closely of the same size, for in a large trough a rigorous uniformity of diameter of fog particle and possibly of distribution is implied, if the corona is to be sharp and brilliant. Particles of even slightly different sizes would give a blurred effect or a mere fog. Therefore, as I understand it, the effect of ordinary dust to some degree vanishes from the corona, and the nucleation observed is probably something more definite. It is for this reason that in spite of very discouraging drawbacks my interest in the subject has not waned, though I am well aware that the effect of chemical products of combustion in winter, such as sulphuric acid, or ionized matter in general, has not been eliminated. One may note, for instance, that the distribution of atmospheric electrical potential is a maximum in winter and falls off in its yearly period in a way similar to the observed nucleation; that there is frequent occurrence of day minima in both cases; that maximum nucleation occurs, as shown in Chapter IX, during the winter months, when one must certainly anticipate the maximum of dust contents during the summer.

The subject of atmospheric nucleation, as a whole, has received enhanced interest in view of its bearing on Arrhenius's theory of the geophysical importance of cosmical, and in particular of solar dust. Some limitation has been put on the light-pressure theory of Schwarzschild, but this has rather stimulated Arrhenius to give a sharper expression of his views, and the theory now appears as the central feature of an admirable discussion of cosmical physics.[1]

I hoped therefore by aid of the present method to *eventually* add a contribution of my own.

2. *Apparatus.*—This consists of a rectangular box, *AA*, 50 cm. long, 15 cm. in thickness, and 10 cm., or preferably less, in height, made of some material impervious to water. Wood covered while warm with a thick coating of wax and burgundy pitch answers the purpose very well, and is much lighter than rigid metallic vessels. The front and rear faces of the box are of thick plate glass. This must be kept clean on the inside, and suitable scrapers with a vertical straight edge of soft rubber movable to and fro along the glass by aid of a long horziontal rod should be provided within the box. The rods pass

[1] *Lehrbuch der Kosmischen Physik*, Vols. I. and II. Leipzig, Hirzel, 1903.

out through perforated corks in the tubes *c*, one on each side, with additional protection to secure an air-tight joint when not in use.

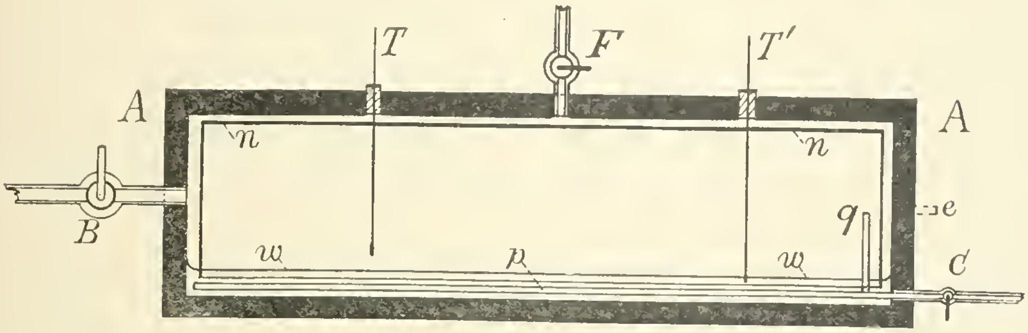


FIGURE 1.—CONDENSATION CHAMBER. SECTIONAL ELEVATION.

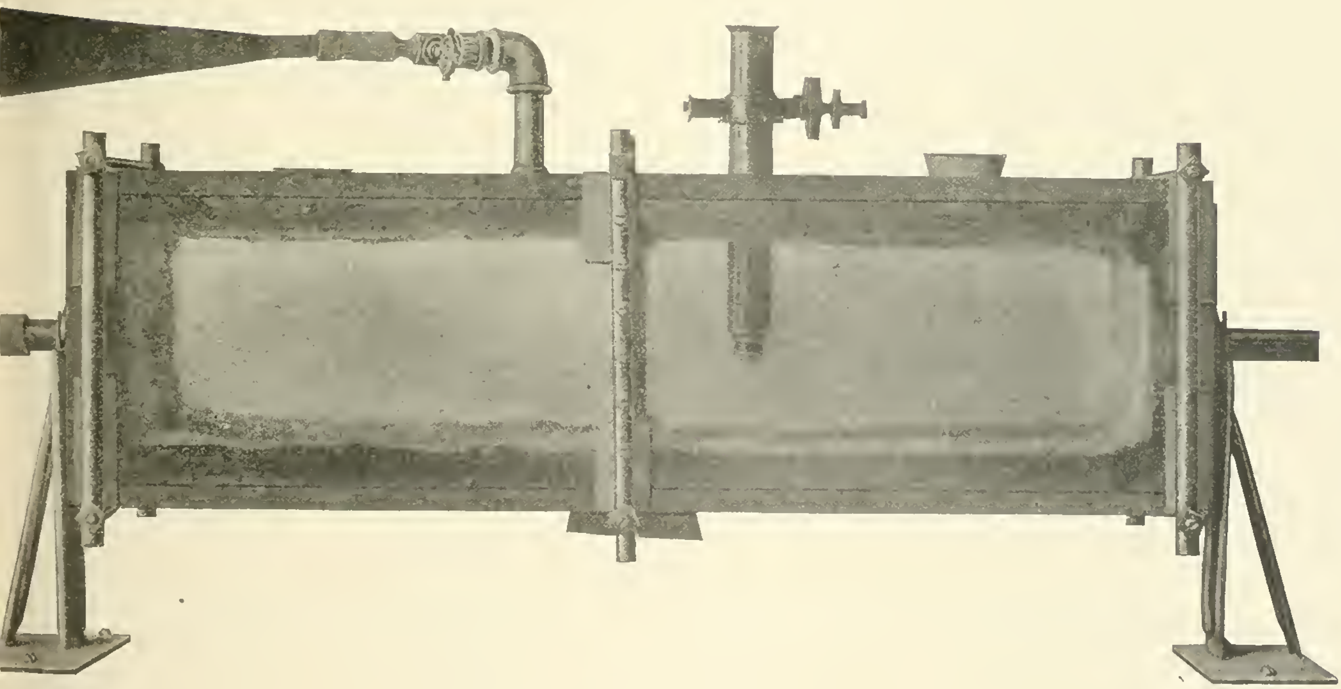


FIGURE 1*a*.—THE SAME IN FULL

The air within the box communicates with the outside by three or more stopcocks, of which B is very wide (more than $\frac{1}{2}$ inch in bore) in order that sudden exhaustion may be made through it. The stopcock C communicates with the atmosphere at a place free from local nucleation, through a length of $\frac{1}{4}$-inch lead pipe; C furthermore communicates with the interior of the box through a flat coil of the same lead pipe, p, lying in the bottom of the trough below the water-level, ww. A coil of lead pipe in a water bath may also be inserted on the outside of the box, the object being to heat the air to room temperature, especially in winter.[1] Two thermometers, T, T', with their bulbs respectively in the air and the water within the trough, register the temperature. The end of the influx pipe rises to a height q, near the axis of the trough and opposite to the outlet, C. Finally, the whole inside of the trough is lined with a double layer of cotton cloth, $n\ n$, supported on a framework of stout copper wire. The trough should be mounted with its longitudinal axis on trunnions in order that the whole interior may be moistened in a single rotation, as shown in figure 1 a, in detail. The stopcock F, provided with a cotton filter, is often useful in testing.

The horizontal diameter of the coronas is observed, the point source of light being about 2 meters off on one side and a suitable goniometer about one meter on the other side of the trough. The distances used were 85 cm. and 250 cm. With the eye at about 1 meter from the fog chamber the apertures of coronas are relatively independent of this distance and at the same time large enough for satisfactory measurement.

An ordinary jet pump suffices for aspiration (with the cocks C and B open); and with an added vacuum chamber provided with a vacuum or mercury gauge, for sudden exhaustion (C and B having been closed), care being taken that the connecting tubing beyond B is wide. These details are shown above.

3. *Diffusion from two opposed surfaces.*—The high values of nucleation observed during the winter months will not be received without misgiving, since the air during the very cold weather is nearly dry, and after being heated to 20° very far from saturation. Deficient saturation, however, would decrease the size of the fog particles and, *cæt. par.*, increase the size of the coronas, in this way showing the same result as excessive nucleation. Hence it is necessary to estimate the time which is needed to saturate dry air in the apparatus described in § 2.

Given a rectangular trough at the bottom of which is a surface of water and at the top of which a surface of saturated cloth, the diffusion problem is equivalent to the case of an indefinite air plate into which the vapor enters on the two exposed sides. Thus if p be the vapor pressure relative to saturation at a distance x above the surface of the water or $a-x$ below the wet cloth, at the time t,

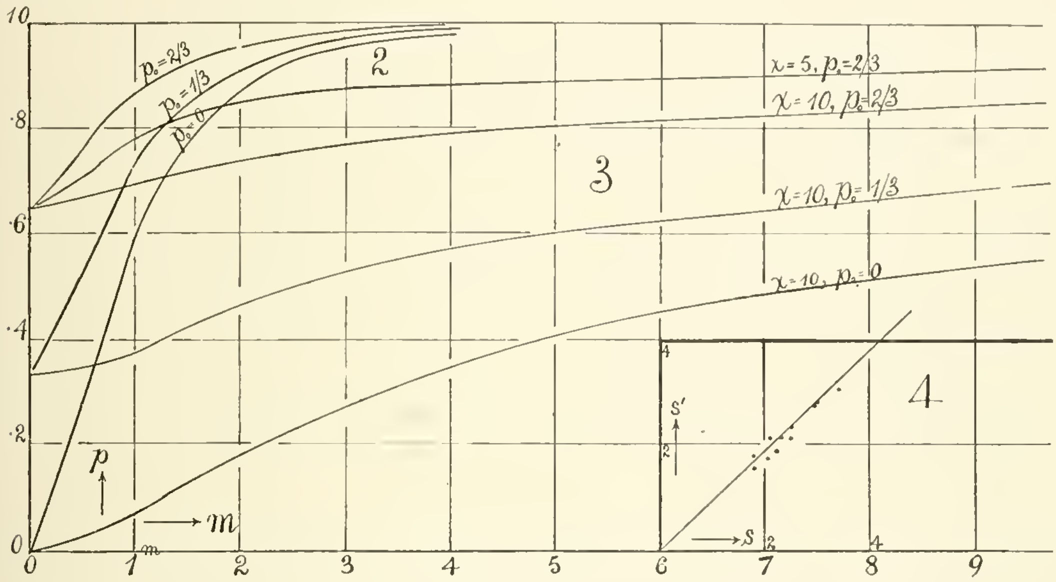
$$p = 1 - \frac{4}{\pi}\left(\sin\frac{\pi x}{a}\varepsilon^{-(\pi/a)^2 kt} + \frac{1}{3}\sin\frac{3\pi x}{a}\varepsilon^{-(3\pi/a)^2 kt} + \ldots\right)$$

where k is the coefficient of diffusion.

If diffusion takes place into a partially saturated atmosphere at an initial pressure p_0, the factor $4/\pi$ in the last equation is to be replaced by $(4/\pi)(1-p_0)$.

[1] In case of a moderately long (20–30 feet), thin ($\frac{1}{4}$ inch) influx pipe, experience showed that both the internal coil, p, and the external coil are superfluous. They were therefore discarded.

The question is most conveniently stated for the middle plane, $x = a/2$, inasmuch as the saturation here is least. Since at 20°, $k = .23$ cm²/sec., about, the results, if $p_o = 0$ initially, are shown in table 1. If the initial saturation is $p_o = 1/3$ or $2/3$, the data, as the table shows, imply successively greater saturation throughout than in the preceding case. As the relative saturation left after any exhaustion would not probably be less than 2/3 even in the absence of convection, the inferior limit of saturation shown by these data is excessive.



FIGURES 2, 3, 4.—GRAPHS SHOWING THE PROGRESS OF DIFFUSION IN THE LAPSE OF TIME.

The upper graphs, figure 2, contain the relative saturation pressures as ordinates at the times given by the abscissas in minutes, according as the initial pressure is $p_o = 0$, $p_o = 1/3$, or $p_o = 2/3$.

TABLE 1.—DIFFUSION OF WATER VAPOR BETWEEN OPPOSED SURFACES; $a = 11$ cm., $x = 5.5$ cm., $k = .23$.

$p_o = 0$		$p_o = 1/3$		$p_o = 2/3$	
t	p	t	p	t	p
30 sec.	.277	30 sec.	.516	30 sec.	.762
60	.587	60	.722	60	.864
120	.866	120	.910	120	.956
180	.957	180	.971	180	.986

Thus in 3 or 4 minutes the air plate in the trough may be considered saturated under the most unfavorable conditions. In the aspiration of fresh air through the trough the maximum rate was about 4.5 lit./min., the usual rate

1.5 lit/min. The capacity of the trough, including parts above the cloth lining, was about 11.3 liters. Hence 3 to 5 minutes suffice to renew the air, and each particle remains in the trough from 1.5 to 4 minutes. The time needed for adjustments after the influx pipe was shut off and prior to sudden exhaustion was about 1.25 minutes. Therefore the total time for saturation was 2.7 to 5 minutes, which should fully suffice even in case of diffusion alone.

The conditions, however, are much more favorable as the influx and efflux currents evoke considerable convection. The lightness of water vapor is itself favorable to the same end. It is observed, for instance, on exhausting immediately after the introduction of phosphorus nuclei, that filamentary condensation is in evidence, denoting currents upward axially and downward near the walls of the receiver.[1] These fog strands are the inevitable convection currents due to the relatively low density of the vapor.

4. *Miscellaneous tests.*—If there had been under-saturation the coronas found on condensation should have been larger in non-saturated and smaller in more saturated parts, which was not observed. Sudden exhaustion immediately after shutting off the influx showed a somewhat enlarged uniform corona, but even enlargement was not invariable.

Whether the fast or the slow influx specified was adopted proved to be without marked effect for reasonable differences of time, *i. e.*, such as would not imply time losses of nuclei.

The effect of a long influx pipe (10 meters of ¼-inch lead pipe) and of a short pipe 1 meter long could not be sharply differentiated, owing in a measure to the cotemporaneous variation of atmospheric nucleation. So the presence compared with absence of the coil in the water bath (24 turns each about 3.5 cm. in diameter) showed a negligible difference.

Experiments were made with regard to the usefulness of this coil for keeping the influx air at room temperature both by filling the bath with abnormally hot water (40° C.) and with broken ice. The effect on the apertures of the coronas was in both cases of little importance. Hence, except on very cold days, the water bath and coil may be withdrawn altogether. The atmospheric air after traversing the 10 meters of influx pipe is already sufficiently heated to be introduced into the condensation chamber directly.

Tests were also made with a U-tube loosely filled with wet sponges and with a drying tube one meter long containing phosphorus pentoxide. In neither case was a definite effect on the coronas ascertained.

Freedom from leakage was finally tested by filtering the air. The coronas on sudden exhaustion showed a gradual decrease to complete evanescence.

5. *Diffusion from a single surface.*—The case is naturally less favorable if the upper wet surface (double cotton cloth) is omitted. The computation may be made from an expansion of Kramp's integral, so that

$$p = 1 - \frac{2}{\pi}\left(\frac{x}{(4kt)^{1/2}} - \frac{x^3}{3 \times 1(4kt)^{3/2}} + \frac{x^5}{5 \times 2!(4kt)^{5/2}} \ldots\right)$$

[1] *Smithsonian Contributions*, No. 1373, 1902.

where p is the vapor pressure relative to saturation at a distance x above the surface of the liquid at the time t for the diffusion coefficient $k. = 23$. The data computed suffice to locate the curves which are sufficiently given in figure 3 for $x = 5$ cm. the middle plane, and $x = 10$ cm. the top plane of the trough. When the initial saturation is $1/3$ or $2/3$, the coefficient $2/\pi$ is to be modified as stated above. Figure 3 shows the corresponding results.

If it were not for convection, therefore, such an apparatus would be unsuitable, for even after waiting 5 minutes, the air at the top, $x = 10$ cm., for an initial saturation of $2/3$ is but .8 saturated from diffusion alone.

One might therefore expect to obtain distorted coronas campanulate in outline, small below and large above, whenever condensation is produced within a few minutes after closing the inlet. Yet such is never the case if less than a minute is allowed after influx ceases. Granting that 2 to 4 minutes are needed on the average for a particle to pass through the trough, as stated above, if exhaustion is made immediately after closing, the top layer is but $2/3$ saturated. Under these conditions there is in fact an unusually large green centered faint corona with a horizontal band of crimson color running through it. Half a minute later, however, the figure is quite regular again, showing that the convection of light vapor must be very active. After 2 minutes subsequent to the closing of the influx pipe, the air may be regarded saturated except in the coldest weather.

6. *Absorption and decay of nuclei.*—The losses in the influx pipe are difficult to determine because of the variation of atmospheric nucleation. The observer is left in doubt whether a given difference is due to absorption in the pipe or to causes without. The experiments incidentally made throughout the long experience of Chapter IX showed no serious discrepancy.

The possibility of loss of nuclei on contact of dry air with the saturated gas in the condensation chamber is an independent question. It is also to be borne in mind that nuclei may possibly be produced by the sudden contact within the chamber. No evidence is forthcoming.

If the nuclei after being introduced into the receiver are solutions, some estimate of their persistence may be formed from my experiments on solutional nuclei, by treating the loss as if it occurred at the boundary of the vessel only. If the nucleation falls off from n_0 to n in the time t, and k is the absorption coefficient,

$$n/n_0 = \varepsilon^{-2(1/r + 1/l)kt},$$

where r and l denote the radius and length of the cylinder in which absorption takes place. In case of comminuted pure water, $k = 5$ to 10 cm./min., and the nuclei should quite vanish in a few minutes.

$t = 1$ min.	$n/n_0 = .154$
2	.023
3	.003

If the nuclei are derived from very dilute solutions, like river water, an average value $k = .1$ may be taken, whence if

t = 1 min.	n/n_o = .96
3	.89
5	.83
10	.68
50	.15
100	.02

The reduction within 3 minutes will not exceed 10 per cent., which would usually lie within a given type of corona. The datum $k = .1$, moreover, corresponds closely to the values found for phosphorus and other nuclei. Hence, if the type of corona changes after 1 or 2 minutes' waiting, it may be considered certain evidence that the air is not saturated and the diffusion error predominates. Owing to the difficulty of avoiding either insufficient saturation or excessive time losses, some of my observations in Chapter IX contain data for two different aspirating currents, the faster corresponding to about 3 minutes' sojourn of the nuclei in the receiver, the other to a time longer than 5 minutes. In this way the effects of under-saturation which are most to be feared are guarded against, while the faster current gives data falling short of the absolute nucleation by not more than 10 per cent. In the course of time this also was abandoned as superfluous.

7. *Effect of pressure difference.*—It is next to be considered whether the pressure difference, δp, used in the exhaustions is pronounced enough to catch all the nuclei. This is of particular interest as a safeguard against low numbers in the nucleations obtained.

The usual value, $\delta p = 17$ cm., corresponds to the following pressure ratios and adiabatic temperature reductions in air, $((76-p')/76-p'-\delta p))\div^{.41}273 = \vartheta'$ if p' is the vapor pressure of water and ϑ' the reduced absolute temperature.

10°	Pressure ratio, 1.292	ϑ' = 254.7
20°	1.297	263.4
30°	1.341	268.8

For comparison data were gathered with a larger pressure difference, δp = 22 cm., for which the values are

10	1.414	245.5
20	1.416	254.1
30	1.432	261.5

Clearly, the coronas for the larger temperatures and temperature differences must be smaller, *cæt. par.*, in view of the greater quantity of moisture precipitated. The data for m, the quantity of moisture precipitated per cubic centimeter of saturated air, have been computed by the method of C. T. R. Wilson and J. J. Thomson and are given in the following table 2. Here t_1 is the initial temperature , t_2 the temperature before and t after condensation.

TABLE 2.—PRECIPITATIONS AT DIFFERENT TEMPERATURES AND PRESSURE DIFFERENCES. $y = (p-p')/(p-p'-\delta p)$; $p = 76$.

$\delta p = 8.5$ cm.					$\delta p = 17$ cm.				$\delta p = 22$ cm.			
t_1	t_2	t	$m \times 10^6$	y	t_2	t	$m \times 10^6$	y	t_2	t	$m \times 10^6$	y
°C	°C	°C	grams		°C	°C	grams		°C	°C	grams	
10°	−3.4	+3.4	2.1	1.12	−18.3	− 4.5	3.7	1.27	−27.5	−10.1	4.2	1.39
20°	+5.8	14.7	2.6	1.11	− 9.6	+ 8.8	4.6	1.26	−18.9	− 4.6	5.5	1.38
30°	15.8	25.7	2.8	1.10	− 4.2	19.6	5.7	1.24	−11.5	17.0	6.7	1.35

Since $m = n\pi d^3/6$, if there are n fog particles per cubic centim. each of the diameter d, and since $sd = D$ where s is the aperture of the coronas with an arbitrary goniometer and D the corresponding constant,

$$s\sqrt[3]{m} = .524D\sqrt[3]{n},$$

which is constant for a given nucleation. Thus the relation between s' and s at $\delta p = 22$ cm. and 17 cm., respectively, may be written

$$s'/s = (m/m')^{1/3} = .952.$$

In figure 4 the line s'/s has been constructed and the observations grouped with reference to it, showing that the curve reproduces the experiments fairly well. The exceptional cases are all too low; or, in other words, at the higher pressure difference, $\delta p = 22$, which requires a longer period of waiting after influx ceases, relatively fewer nuclei are entrapped. From this one concludes not only that from the medium, if saturated, all the nuclei are precipitated at $\delta p = 17$, but that at the higher pressure difference the time needed for adjustment is excessive and that the time loss of nuclei in the receiver frequently becomes appreciable.

On the other hand, if δp exceeds 22 cm. for the given apparatus, the conditions of spontaneous condensation of dust-free moist air are initiated and continue thereafter with increasing intensity for higher pressure differences.

8. *Precipitation per cubic centimeter.*—To determine m, I have heretofore proceeded as follows: In a mixture of x grams of vapor, y grams of air, and $1-(x+y)$ grams of water, the absorption of heat due to a rise of temperature $d\vartheta$ at constant volume was taken as $C(1-(x+y)) + hx + r\,dx/d\vartheta + cy$, per degree, where C, c, and h are the specific heats of water, air at constant volume, and saturated vapor, respectively, and r the latent heat. Since $h - C = dr/d\vartheta - r/\vartheta$, h may be eliminated. Again the absorption of heat due to a volume increase dv, at constant temperature is if γ is the heat ratio $r\,(dx/dv)dv + y\vartheta c\,(\gamma-1)dv/v$. If the expansion is adiabatic the total heat absorption is nil and the equation thus obtained may be reduced eventually to

$$\frac{d}{d\vartheta}\,(rx/\vartheta + (C(1-y) + cy)lg\vartheta)d\vartheta + yc(\gamma-1)d\lg\vartheta$$

As this is not a perfect differential I assumed the relation of v and ϑ to be approximately that of air, $v^{\gamma-1}\vartheta$ = const., supposing that I could subsequently correct for the precipitated water by successive approximation. In this way one obtains at the beginning and the end of the exhaustion for any two temperatures ϑ and ϑ' (using accents throughout for the latter case), after integrating, $x'/x = (\vartheta'/r')(r/\vartheta - lg(\vartheta'/\vartheta))$, where $(x-x')/x$ is the mass ratio of precipitated liquid to the original vapor. In my work thus far[1] the results computed in this way and for $\delta p = 17$ cm. were at 10°, 20°, 30°, $m \times 10^6 =$ .59, 1.13, 1.85 grams, respectively, where the corrections for precipitated moisture have been applied and δp is an isothermal value. If δp, the observed pressure reduction, were treated adiabatically the corresponding values of $m \times 10^6$ would be .42, .76, 1.28.

The results for m so obtained will have to be rejected as they are much too small (probably because the pressure coefficients were overlooked) when compared with the more direct approximation of Wilson and Thomson. The value of m is here found as an intersection by making the m values compatible with the vapor density curve for water. These data have already been computed for the pressure difference $\delta p = 17$ above, table 2, and will be used in Chapter IX.

9. *Relation of nucleation to aperture of corona.*—A summary of the method of deducing the nucleation (number of nuclei per cubic centimeter) from the observed coronal aperture for an observed pressure difference ($\delta p = 17$ cm.), in the given apparatus, has already been fully explained in Chapter VII, § 26, and needs but little further reference here.

Measurements of the aperture s would naturally be made as far as the inside of the red ring or the circumference of the eventually white disc; but in such a case they bring out very strong periodicity in the first place, and are soon subject to large errors due to the increasingly vague and washed outline of the disc. Hence measurement is more appropriately made to the dark blue ring which limits the green coronas or to the dark interior of the green ring in the crimson coronas. These lines are not only sharper but they reduce the periodicity. It is understood that with air nuclei and $\delta p = 17$, the green corona is seldom exceeded. Otherwise it would be necessary to increase the uniform pressure difference, against which there is no objection other than the increased practical inconvenience, provided the pressure difference for which saturated air condenses spontaneously (above $\delta p = 22$ cm. in the above apparatus) is not exceeded.

10. *Absence of electrification in cases of sudden condensation and of sudden evaporation.*—It has long been known as the result of most painstaking observations, that neither in cases of ordinary evaporation nor of condensation is there an accompaniment of electrification. On the other hand, when a mass of water is suddenly shattered, as in jets, the electrification is marked, while it is

[1] *Smithsonian Contributions to Knowledge*, No. 1373.

not obvious that the underlying cause is friction. The electrification soon vanishes, however, whereas the nucleation persists. The question thus arises, therefore, whether in ordinary slow evaporation the absence of an electrical effect may not be due to the possibility of charges vanishing too quickly to be noticeable. It seemed worth while, therefore, to examine the case for the *sudden* condensation and the rapid evaporation of fog particles.

To test this question a graduated electroscope was introduced into the condensation chamber. To insulate it in the saturated atmosphere, the stem was enclosed in a hard rubber tube, as in figure 5, open below and only in contact with the stem at the top by a sealing-wax joint. The tube was thoroughly dried before insertion into the condensation chamber, and the instrument showed satisfactory insulation for a half-hour or more, after which it was removed for desiccation prior to new experiments.

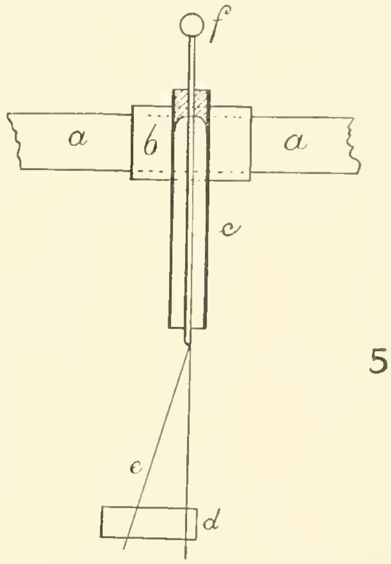


FIGURE 5.—APPARATUS TO DETECT IONIZATION PRODUCED BY SUDDEN CONDENSATION.

Condensation was produced by exhaustion as usual, and the nuclei used were obtained from air as well as from phosphorus. The method of procedure consisted in observing the normal leakage of the charged electroscope by observations made every half-minute. Nuclei were then introduced and the experiment repeated with the alternate sudden production and sudden dissipation of fogs between each observation.

The two curves of leakage were not distinguishable, even when the fogs were of the densely opaque character due to phosphorus, and the error of the method was about 5 per cent., with somewhat larger uncertainty for the case of fog evaporation.

Pressure differences, however, were kept below the limit (much above $\delta p = 22$ cm. in the given apparatus) at which saturated air spontaneously condenses without nuclei. This phase of the question, which in fact is rather the more interesting one, is thus left at issue. If, for instance, dust-free air is always slightly ionized and thus contains unstable systems, the increase of ionization by sudden exhaustion in virtue of the unstable molecules referred to is by no means excluded. The question has been touched above.

11. *Conclusion.*—In the above paragraphs I have endeavored to present the complications to which the method of coronal registry of atmospheric nucleation is incident, complications which were not anticipated and for which I was altogether unprepared. In the course of my work I made several unfortunate blunders in endeavoring to reduce the data to absolute values, but apart from these the greater number of discrepancies (as, for instance, the periodic distribution of nucleation in terms of aperture) could not have been foreseen at the outset.

With regard to atmospheric nucleation, it seems to me, in addition to the remarks made in § 1, that the variety and importance of the phenomena which are now attributed to the invasion of solar and cosmical dust into the atmosphere, such as certain variations of atmospheric pressure, of atmospheric electricity, of terrestrial magnetism, of auroral display, etc., induce one to wonder why continuous and systematic records of atmospheric nucleation, other than the series obtained at Ben Nevis during the period when Aitken's observations gave to the subject widespread interest, have not long since been included among the records of observatories. Surely in discharging its remarkable and varied cosmical functions, this dust from afar, if at all persistent, must some day be detected undisguised.

CHAPTER IX.

THE NUCLEATION OF THE ATMOSPHERE OF THE CITY OF PROVIDENCE.

INTRODUCTION.

1. *Preliminary.*—In May, 1902, Mr. Harvey Davis, at my request, put up an apparatus in the laboratory of Brown University for counting the number of nuclei in the atmosphere, by measuring the coronas producible with such air under appropriate conditions. The apparatus gave promise at once; but Mr. Davis was unexpectedly called away before the observations became fruitful, and the project was temporarily abandoned. Believing that an instantaneous method of at least estimating the degree of atmospheric nucleation is a desideratum, and must throw light eventually on the origin and character of the nuclei in the atmosphere, I have undertaken the furtherance of the work myself, and the results obtained since October, 1902, after the indications of the apparatus had become warrantable, are given in the present chapter. I may add that Mr. Davis and Mr. R. Pierce, Jr., had been at work for some time on the measurement of the daily variation of the solar constant (a project then set on foot by the U. S. Weather Bureau), and that I had hoped from the coordination of the two classes of data to reach conclusions of interest.

The chapter, therefore, contains nearly two years of continuous record of the nucleation of Providence, R. I. The observations were made in the park of Brown University, which is surrounded, however, on all sides by the city. The density of population lies to the west and southwest. A station entirely away from the habitations of man would naturally have been preferable, but this desideratum was at the outset out of the question.

2. *Apparatus.*—The apparatus and method by which the present results were obtained are fully given in the chapters above, particularly in Chapter VIII, and need not therefore be further considered here. In figure 1, however, I have shown a simplified train of apparatus used in some of my early work (October 2, 1902, to March 15, 1903). Here d is the influx tube, B the water-bath at room temperature, t the thermometer, A the condensation chamber (the water w is made to wet the sides by rotating A before expansion), R the vacuum chamber, G the gauge, S the pipe to the suction pump. Stopcocks b and c control the exhaustion, together with a.

3. *Classification of results.*—The results themselves may be embraced in two groups. The first group of observations, from October 2, 1902, to March

15, 1903, were originally made with reference to an arbitrary scale of nucleation. There are many reasons why it would be difficult to reduce them accurately to the uniform scale of the present chapter. Among these, frequent changes of apparatus, measurement of aperture to the red ring, and the absence of a variety of details of record discouraged such an attempt. The reduction, therefore, is approximate; but the values of nucleation are roughly absolute and quite

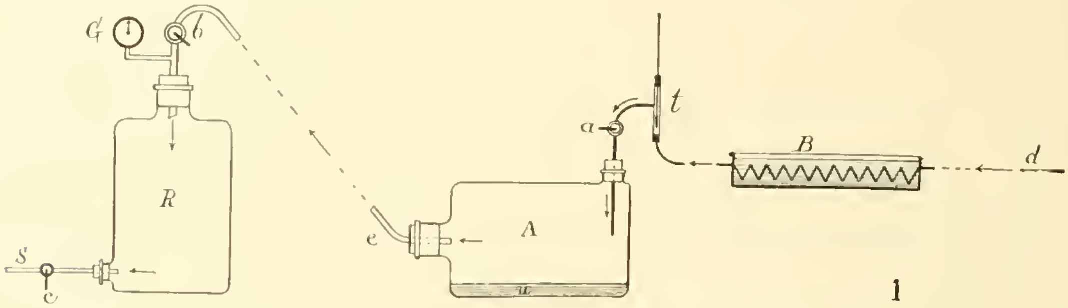


FIGURE 1.—DIAGRAM SHOWING GENERAL DISPOSITION OF APPARATUS.

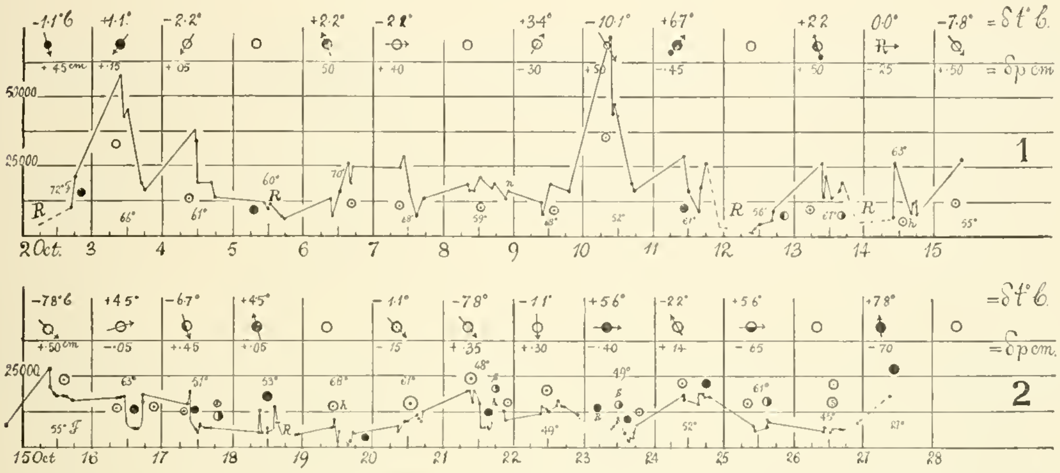
satisfactory as relations, and they thus meet most of the demands made upon them. In view of their preliminary character they will be given in charts only. In these cases the condensation chamber was a large aspirator flask (fig. 1), placed horizontally so that the measurement of aperture was made parallel to the axis of the cylinder.

The second group of observations (by far the larger number) from March 15, 1903, to October 31, 1904, were obtained with apparatus perfected as explained above. These will therefore be given both graphically and in tables. The latter will contain a variety of relevant data.

FIRST GROUP OF OBSERVATIONS.

4. *Early observations.*—The charts Nos. 1–12, comprehending the first group of results, follow. The nucleations, n, are laid off vertically, and in charts 1–8 they are given in full (n nuclei per cubic centimeter). In the remaining charts (Nos. 9, *et seq.*) the number of nuclei are given in thousands ($n \times 10^{-3}$) for brevity. The temperature and winds (for 8 A.M.), taken from the weather maps of Block Island and Nantucket, will often be entered, but as the work progressed superfluous data were gradually dropped. In some of the charts the changes of temperature, δt, and of barometric pressure, δp, are also given, with the occurrence of clear weather, ⊙, cloudy, ● and partly cloudy ◑ weather, sunshine S, rain R, snow Sn, cold wave c.w. or $-$ ⸗, etc. References to Fahrenheit and to centigrade are indicated.

The nucleation (chart 1) begins low on the 2d of October, 1902, with the rain, but thereafter increases nearly fourfold with the bright weather of the succeeding days. Note the prevailing winds from the north on the 5th and 6th, clouds and rain usher in a second minimum. On the fair days succeeding the nucleation is not as high as before until the 10th, when a sudden enormous increase occurs, cotemporaneously with fall of temperature. The high maximum is succeeded by an equally low minimum, brought on by the rainy weather of October 11 and 12. The nucleation then rises during the succeeding fair days, to fall to a fourth minimum during the rain of October 14. No doubt



Charts 1–48.—Daily Observations of the Atmospheric Nucleation of Providence. Number of Nuclei (n) per Cubic Centimeter, Laid off Vertically. In Charts 1–8, n is given in Full In Charts 9–48, n is given in Thousands per Cubic Centimeter. Charts 1–12, are Reduced from an Older Arbitrary Scale. Local Winds, Rain (R), Temperature, etc., are Given in the Charts, Arrows Showing the Direction in which the Winds Blow. Clear ⊙, Partly Cloudy ◑, and Cloudy ● Weather, etc., are Indicated with the Usual Signs.

some variation is due to the variation of the temperature of the apparatus, for which no correction[1] was made, but the rain and fair weather effects as a whole are unmistakable. The maxima on the 4th and 10th correspond to anticyclonal conditions.

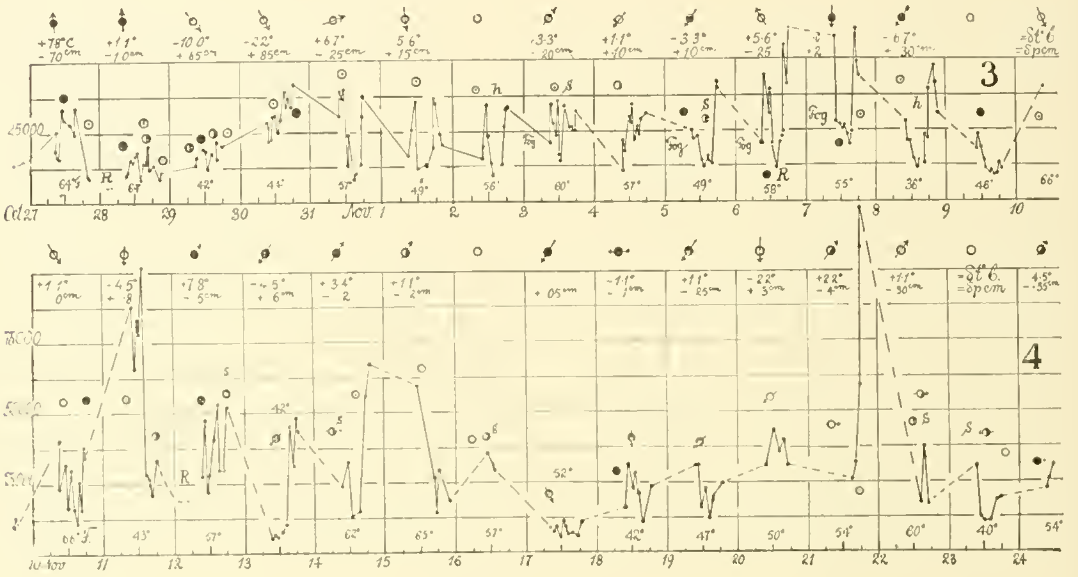
The apparatus was now modified in a way which need not here be instanced. What is noteworthy in the next data (chart 2) is the occurrence of sharp minima on October 16, 17, 21, 23, cotemporaneous with the passage of dense cloud masses over the sky. In three of these cases the curve rises as soon as the sky clears; on October 17 it does not do so, but the curve runs into the overcast condition of October 18. The pronounced minimum on October 19 during clear weather shows that sunshine can not be a reason for an abundance of nuclei. Similarly there is high nucleation on October 24 and 27, simultaneously with an overcast sky. A number of night observations on October 18 give no evidence of unexpected behavior.

On October 27 the apparatus was again modified, by substituting a long cylinder for the aspirator flask thus far used as a condensation chamber. The data (chart 3) begin with high nucleation for an overcast sky and fall off to the rain storm on October 28. The high nucleations are very fluctuating,

[1] Correction for temperature was applied at a later date, but thereafter again abandoned as untrustworthy.

which would be even more apparent if night observations had been made. The cause is obviously convection, and the diagram necessarily presents marked similarity to a wind curve.

The feature of the data from November 1–10 (charts 3 and 4) is the ten-



Charts 3 and 4.

dency to notched minima at mid-day or in the early afternoon. The maximum on the 11th coincides with a slight drop in temperature, but beyond this the temperature is so nearly constant until November 24 that reasons for the variations of the figure are not forthcoming. The remarkable rise on the 21st may

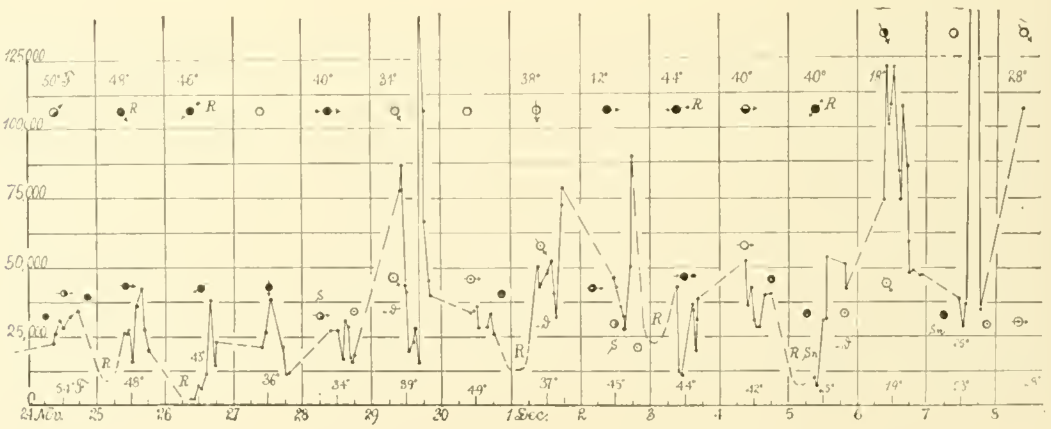


Chart 5.

be noticed. On November 14 and 23 there are mid-day minima, but others are not apparent. During the remainder of November (chart 5), rain minima occur on November 25, 26, and at the end of November 29. The maximum on

November 29 is clearly associated with the drop in temperature, and there is here one mid-day minimum but no others.

Throughout December cold waves associated with northwesterly winds are productive of maxima. After the rain of December 1 the nucleation rapidly rises, accompanying a second drop in temperature. The maximum is moderately sustained until the 3d, where there is fall into the rain minimum, partial recuperation thereafter, and then another drop into the rain of the 5th.

This rain soon changes into snow and from here the nucleation (chart 6) of the cold wave begins, lasting from the 6th to the thaw on December 11. One

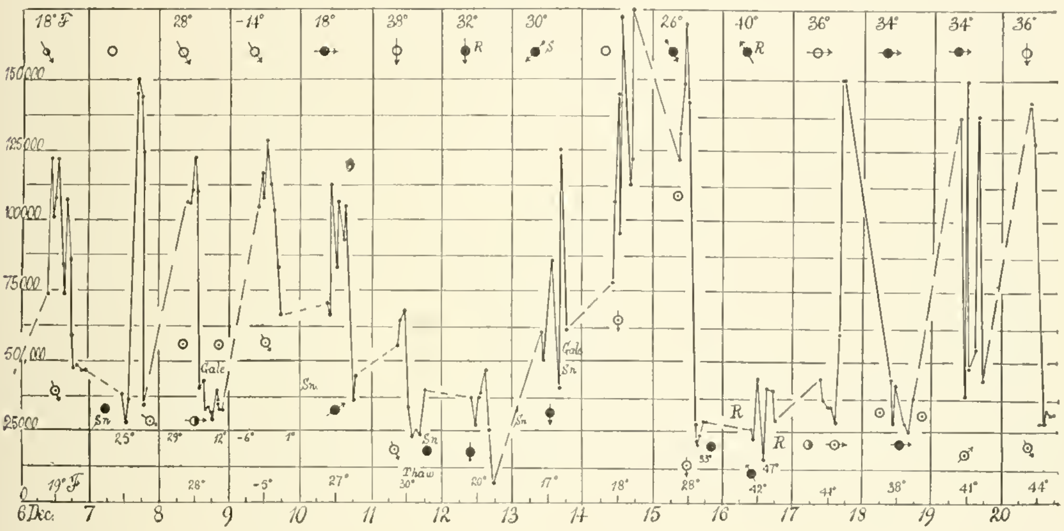


CHART 6.

may note the reduction due to very cold snow on December 7, and the curious minimum accompanying the gale on the evening of December 8. The maxima on the 9th and 10th accompany northerly winds and a drop in temperature. The very remarkable maximum from December 13 to December 16 follows the fall of temperature after the thaw on December 15, introducing a rain minimum. This interesting region is no doubt referable to the snow-storm on the evening of December 13, the winds remaining northerly. The ground was frozen on December 13 and 14. The region is not due to temperature. The maxima on December 17 and 20 are less sustained, but they come with temperatures above freezing and westerly winds. The absence of night observations is a dilemma in these cases. The low nucleation indicated on December 20 continued for several days (December 20 to 23) beyond the limits of chart 6, but is shown on chart 7.

One may regard it as a general rule established by these charts, that the nucleation increases when temperature suddenly decreases, but that temperature is not the sole or ultimate factor involved. To see whether this view would work out in detail, I compared the observatory thermograph data for Providence during the three months (kindly placed at my disposal by my colleague, Prof. Winslow Upton) with the data for nucleation given in the above charts. A limited degree of similarity was in this way made out for cold weather, both in the general march of temperature throughout longer intervals and in its detailed variations. Thus the mid-day minima are obviously counterparts of corresponding temperature maxima. There were, however, many outstanding discrepancies, and it seemed probable that much of this would be referable to local differences, as the observatory is differently situated and at a distance from the laboratory. Beginning with December 28, I have, therefore, been making daily temperature observations simultaneously with the coronal observations, using a long mercury thermometer placed be-

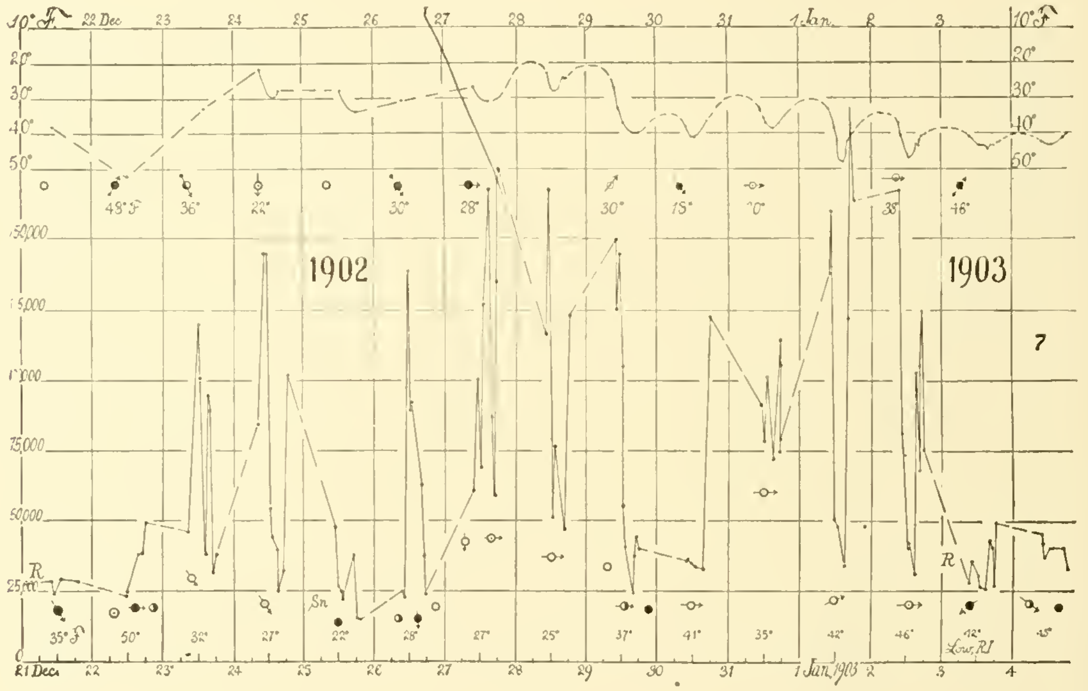


CHART 7.

side the influx pipe. The temperatures are given on the tops of charts 7 and 8, and *positive temperatures in degrees Fahrenheit are laid off downwards* to insure an easier recognition of coincidences, remembering that nucleation maxima and temperature minima correspond.

In the fragmentary temperature observations before December 28 (chart 7) some relation is seen; thus the maximum between December 23 and 25 has a temperature equivalent, the broad minimum on December 22 and the mid-day minimum on December 24 correspond, etc. Turning to the cases under detailed observation, the mid-day minimum on December 28, the fall on December 29, and, to a smaller extent, the data on December 30 and 31 (in the latter case other factors are active) agree. The marked minimum on both cases of January 1 and, to some extent, January 2 are especially striking.

In chart 8 the general maxima marked "c.w." may be noted, and the details are similar. One may point out the marked fall on January 11 and the day minimum on January 14. On this curve there is, however, one good

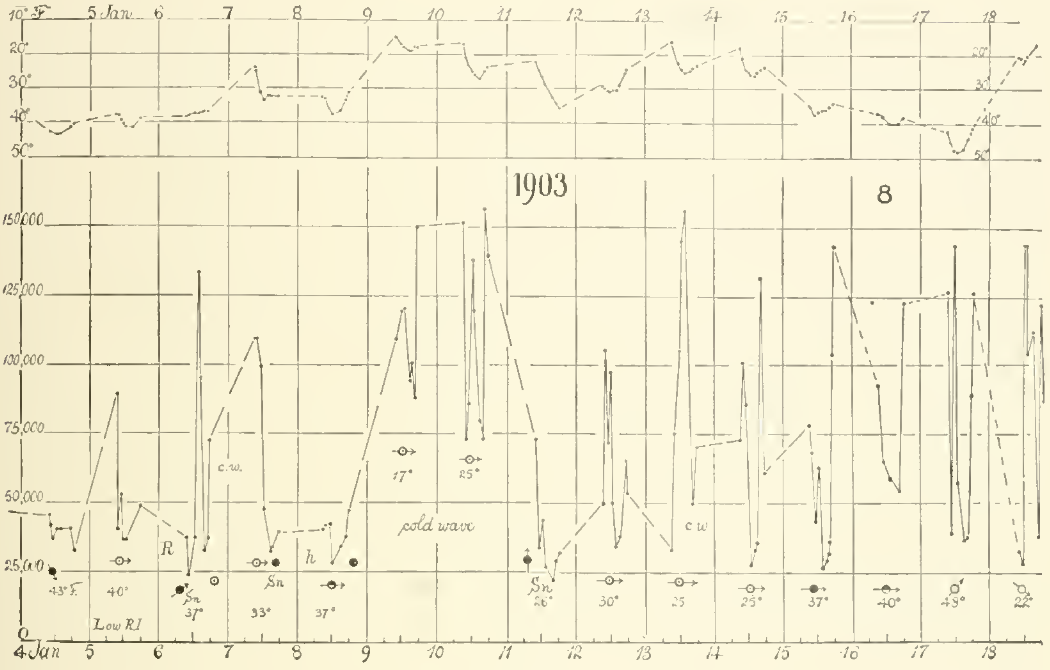


CHART 8.

example of the opposition so frequently to be observed in the summer time, for on January 13 a pronounced minimum of the temperature curve occurs simultaneously with a maximum of nucleation. Again, the marked fall of

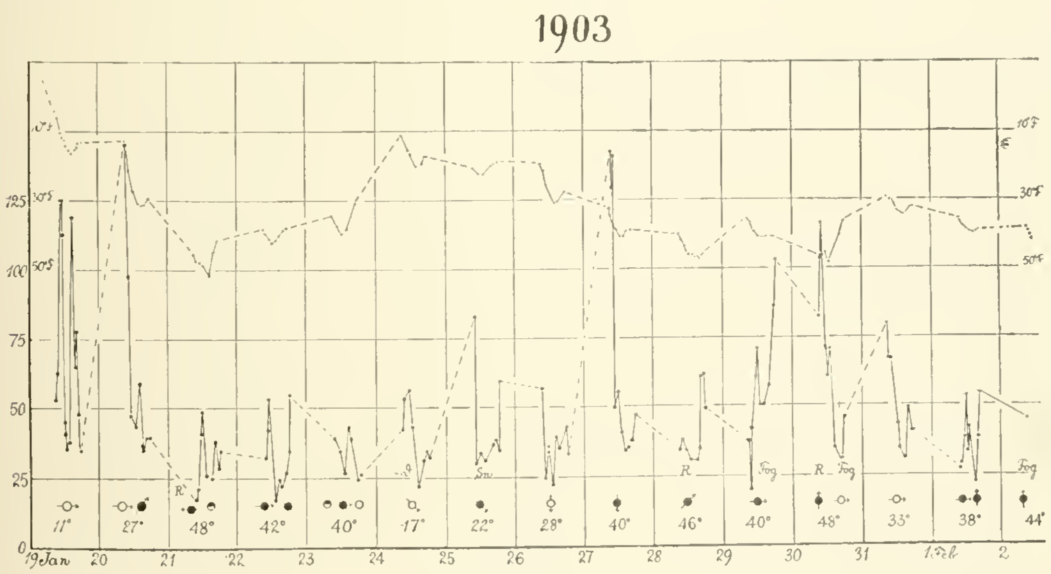


CHART 9.

temperature on January 17–19, both as a whole and in its details, is unaccompanied by a corresponding nuclear effect, and this is true throughout the remainder of January. Leaving the high rain minimum on January 21 (chart 9), the cold wave from January 23–26 produces but a small effect, while the

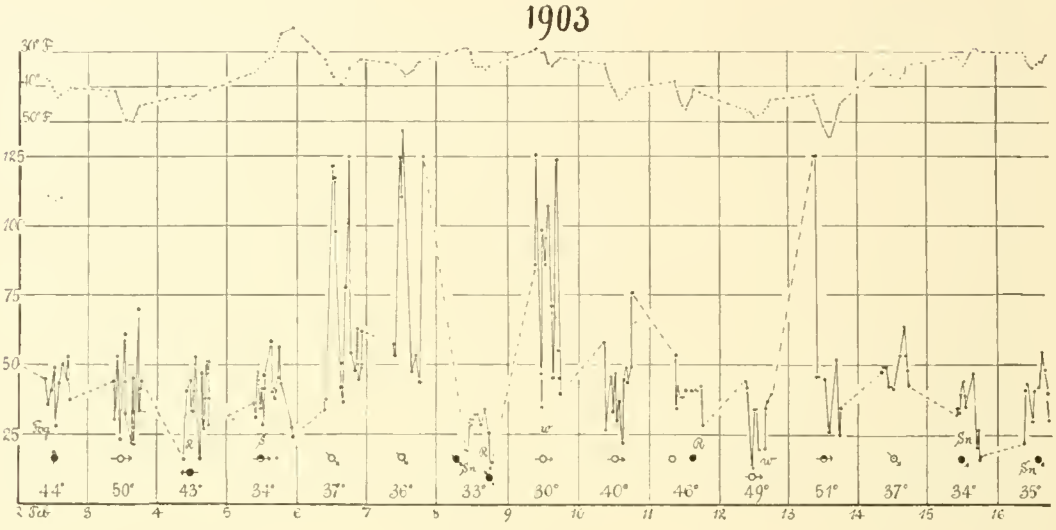
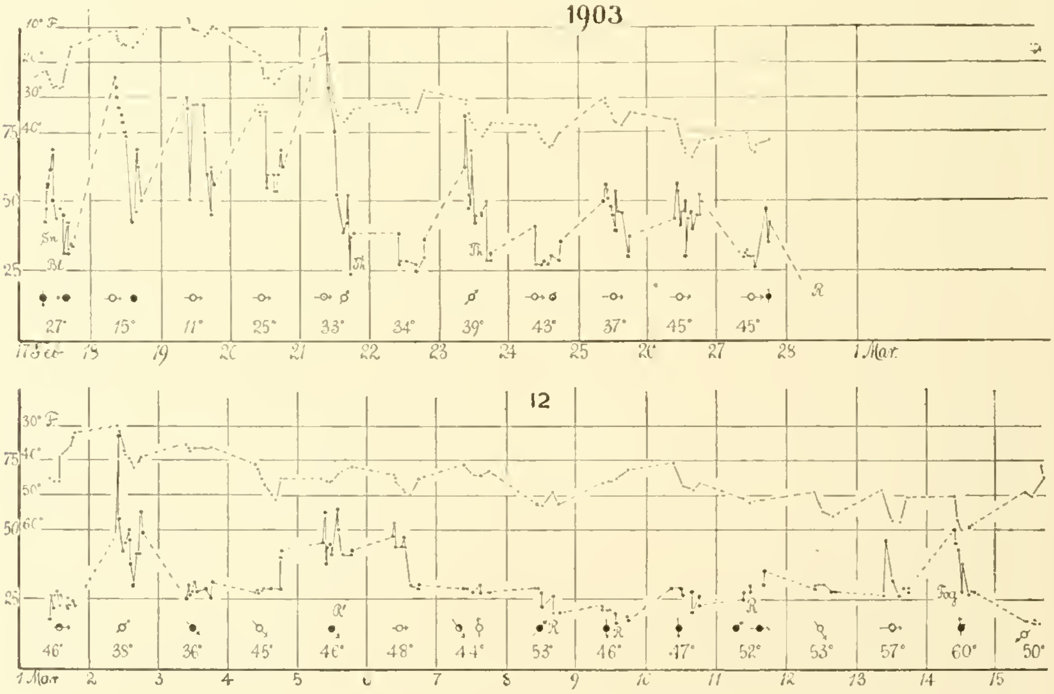


CHART 10.

high nucleation on January 27 is not foreshadowed by the corresponding march of temperature.

5. *Plate glass apparatus.*—Apparatus with plate glass windows was first



CHARTS 11 AND 12.

installed on January 29 and thereafter used permanently. The beginning of February (charts 9 and 10), with its frequent dark fogs and relatively warm weather, shows lowered winter nucleation. The data are numerous because many subsidiary experiments were made, but little of new import suggested.

The method of measuring coronas *to the outside of the first red ring* was adopted on February 16.

The cold wave beginning on February 18 (chart 11) shows moderately high nucleation until it breaks with the thaw on February 21. Thereafter gradual but fluctuating fall of the temperature and nucleation curves appears from February 22 to the intense rain on February 28. During much of the time the ground was covered with snow. Mid-day minima are of common occurrence.

March 1–15 (chart 12), with its relatively high temperatures, has nearly wiped out the characteristic winter nucleation. The daily nucleation is not very variable and the rain minima are curiously high. The temperature effect is quite vague, there being as much opposition as correspondence. This *sudden drop of the winter nucleation in March, 1903*, is particularly noteworthy and it will not be repeated in 1904. The Sunday nucleations in March are not exceptionally low until the 15th, when an abnormally small value for a clear day appears. As there is a general cessation of work in factories on this day, the corresponding nucleations are to be carefully scrutinized throughout the period of warm weather following. During cold weather there is no reduced nucleation on Sunday.

SECOND GROUP OF OBSERVATIONS.

6. *Arrangement of tables and graphs.*—On the 12th of March the same apparatus was installed in a new position, and on March 15 the results referred to above, § 3, as the "second gruop," begin. The scale is uniform throughout, though somewhat enlarged, and the plan is the same as above. Local winds and temperatures only are entered.

The data are also given in tables, as it is believed that the method is now sufficiently definite to make these available for other purposes than the immediate ones of the present chapter. The tables contain the date and hour, the state of the weather, the temperature of the atmosphere where the nucleation is observed in degrees Fahrenheit, and of the air within the apparatus in degrees centigrade; furthermore, the aperture, s, of the coronas when the goniometer radius is 19.5 cm. and the distance of the goniometer and source of light 85 cm. and 250 cm., respectively, from the condensation chamber. Thus the angular diameter is $\varphi = 2\sin^{-1}(s/39)$. The remaining columns contain the coronas with the colors recorded from within outward, abbreviated as stated, and the absolute nucleation, n, or number of nuclei per cubic centimeter of air. Certain obvious remarks will be added.

The correction for the temperature of the condensation chamber (purposely kept as nearly constant as possible) was not applied. This would have enormously increased the labor of reduction, without materially changing the distribution of the nucleation observed. It is to be remembered, moreover, that the true law of reduction is periodic, and unless the periodicity is fully worked out for the small coronas, the temperature correction has little meaning. It is because of this complexity that the tables are very specific as to the color type of the coronas, their size, the temperature of the fog particles, etc. In any special case, therefore, the rigorous reduction (if of interest) may be attempted, but at present there is no call for it.

As to the accuracy of the results so far as the readings are concerned, an error of 2000 to 3000 nuclei per cubic centimeter is unnecessary in the extreme case of large coronas; whereas the whole range of variation is about from 2000 to above 100,000. For the small coronas the reading is correspondingly sharp, and the same is true if a larger goniometer is used.

TABLE 1.—Continuous record of atmospheric nucleation from March 15, 1903, to November 1, 1904. The time (t) is given in hours and tenths of an hour, the temperature of the fog chamber in degrees centigrade, the local atmospheric temperature (approximate) in degrees Fahrenheit. The aperture of the coronas is s, where the angular aperture is $\varphi = 2 \sin s/39$, as the arms of the goniometer are 19.5 cm. long. The last column but one shows the number of nuclei, n, per cubic centimeter of air, using the table in Chapter VII, § 26, for the reduction from s to n. Temperature corrections were not applied. The pressure difference was uniformly $\delta p = 17$ cm. of mercury. The distances of the eye and the source of light were 85 cm. and 250 cm. (1:3), on opposite sides of the condensation chamber. The weather abbreviations are f fair, f′ partly fair, c′ partly cloudy, c cloudy, R′ slight rain, R rain, Sn snow, S sun, etc. The coronal color abbreviations are c (crimson) deep red, r orange red, br brown, o orange, y yellow, g green, b blue, v violet, p purple, etc. A vertical line denotes an indeterminate color, as w r | g; an accent an approach to the color, as r′ reddish; a capital, a deep dark color, as B deep blue, etc. Mixed colors are written together, as bg, blue-green, or, orange-red. Subsidence measurements when entered (November, 1903) are usually abbreviated a/b, meaning that a seconds are required for a fall of the fog line of b centimeters. Sometimes the abbreviation is b/a, as will be stated (April, 1904).

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Apertures.	Corona Colors.	Number n.	Remarks.
1903	Mar. 15	10.3	f	N.E.	20.5	49.2	1.8	w br B	7000	
		10.6	f		20	—	1.8	Do.	8000	
		12.8	f		21	50.4	1.8	Do.	8000	
		1.0	f		21	—	1.9	Do.	8500	
		1.2	f		21	—	2.0	Do.	10000	
		1.4	f		21	—	2.0	w br B g	10000	
		5.2	f		20	44.8	1.9	w br B g r	8500	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Apertures.	Corona Colors.	Number *n*.	Remarks.
1903	Mar. 15	5.4	f		20	—	1.9	Do.	8500	
		6.4	c		20	42.0	1.8	Do.	8000	
			c R′		—	—	1.8	Do.	8000	
	Mar. 16	9.3	c	N.E.	18	41.4	2.4	w br B g	18000	
		9.5	c		18	—	2.6	Do.	22000	
		11.1	c		19	42.6	2.4	Do.	18000	
		11.3	c		19	—	2.5	Do.	21000	
		4.3	c		19	42.5	2.8	w br B p	28000	
		4.7	c		19	—	2.9	w br B r	31000	
		5.9	c		20	—	2.5	w br B g	20000	
		6.1	c		20	40.3	2.5	Do.	20000	
	Mar. 17	9.4	c	N.E.	20	45.8	3.6	w *c* g	57000	
		9.6	c		20	—	3.5	w *c* g	53000	
		10.1	c		19	—	3.1	w br B|p	40000	
		12.6	c		20	53.4	2.9	w br B p	31000	
		12.7	c		21	—	4.0	w r g	78000	
		12.8	c		21	—	3.0	w br B p	37000	
		2.7	c	S.W.	21	58.8	3.1	w br B|p	38000	
		6.1	c		23	56.4	3.1	Do.	38000	
		6.3	c		23	—	3.1	Do.	38000	
	Mar. 18	9.5	c	N.W.	20	49.9	2.1	w br B g r	12500	
		9.7	c		20	—	2.3	w br B	16500	
		11.8	f (S)		21	—	2.3	Do.	15500	
		12.1	f		21	54.0	2.3	Do.	16500	
		4.5	f		22	53.5	2.3	Do.	15500	
		4.7	f		22	—	2.3	Do.	16500	
		5.8	f		22	50.0	2.2	Do.	13500	
		5.9	f		—	—	2.3	Do.	15500	
	Mar. 19	8.7	c	S.W.	19	44.8	3.0	g br B p	35000	
		8.8	c		—	—	3.0	Do.	35000	
		2.6	f (S)		21	66.8	2.9	y br|b	31000	
		3.0	f		21	—	3.4	w br	49000	
		4.1	f		22	—	3.0	w br	35000	
		4.2	f		22	64.6	3.0	w br|b	35000	
		5.7	f		22	57.9	3.5	w *c* g	55000	
		5.8	f		22	—	3.5	Do.	53000	
	Mar. 20	9.2	f′ (S)	W.	20	62.4	3.0	w br B p	35000	
		9.4	f′		20	—	3.8	w r g	66000	
		10.0	f′		20	—	3.5	w *c* g	53000	
		12.8	f′		21	68.5	2.8	y′ br b p	30000	
		1.0	f		21	—	3.5	w r g	53000	
		1.1	f		21	—	3.5	Do.	53000	
		2.7	f		22	71.2	2.7	g′ br B p	27000	
		2.8	f		22	—	2.7	w br|b	27000	
		5.3	f		23	57.9	2.8	w br B p	28000	
		5.5	f		23	—	2.8	Do.	28000	
		6.0	f		23	—	2.8	w *c*|g	28000	
	Mar. 21	9.6	c R	E.	20	46.2	2.4	cor	19000	
		9.7	R		20	—	2.2	Do.	14500	
		10.7	c		20	48.4	3.0	w br B p	35000	
		12.2	c		21	49.8	2.4	w br b′	17500	
		12.9	c		21	52.2	2.3	w br B|r	15500	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1903	Mar. 21	2.9	c		21	54.9	2.9	w br B r	31000	
		3.1	c		21	—	2.6	w br B	22000	
		5.7	c		23	56.0	2.9	w r g	31000	
		5.9	c		23	—	2.8	Do.	30000	
	Mar. 22	9.5	c R′	N.E.	22	51.2	2.0	w br B g	11000	
		10.0	c		22	52.7	2.5	w br B g	21000	
		1.5	c R		22	52.4	2.4	Do.	17500	
		1.6	c R	N.W.	22	—	2.5	Do.	20000	
		6.5	c		21	51.2	2.4	Do.	17500	
		6.6	c		21	—	2.4	Do.	17500	
	Mar. 23	9.0	R	N.E.	20	44.7	1.8	cor	7000	
		9.4	R		20	—	2.0	Do.	11000	
		12.8	c		21	47.6	2.1	Do.	11500	
		12.9	c		21	—	2.1	Do.	12500	
		2.8	R		21	49.0	2.9	r br|bg	33000	
		3.0	R		21	—	2.9	w br B p	33000	
		3.4	R	S.	21	—	2.9	Do.	33000	
		6.1	c R		22	57.8	2.5	w r g	21000	
		6.3	c R		22	—	2.6	w br B g	22000	
	Mar. 24	9.2	c	S.W.	20	57.2	2.8	w|B p	28000	
		9.4	c		20	—	2.7	Do.	25000	
		12.8	c		21	63.2	2.2	w br B g	13500	
		12.9	c		21	—	2.2	w br B g	13500	
		4.0	c		23	60.5	2.7	y′ r g	25000	
		4.7	c		23	—	2.8	g′ B p	28000	
		6.0	c		23	55.0	2.7	w br B g	27000	
		6.1	c		23	—	2.8	w r g	28000	
	Mar. 25	9.5	f	N.W.	20	51.2	2.6	w br	22000	
		10.5	f		20	53.0	2.8	w br	28000	
		11.6	f		20	53.7	2.6	w br	24000	
		12.5	f		20	51.3	{2.8 2.7}	y r|g	28000	
		2.9	c		21	51.0	2.2	w br B	13500	
		3.2	c		21	—	2.2	y′ br B	13500	
		5.8	c		21	47.1	2.1	cor	11600	
		6.0	c		21	—	2.3	Do.	15500	
	Mar. 26	9.5	f′	W.	19	43.5	2.8	w br b	30000	
		9.7	f		—	—	2.8	w br B|p	28000	
		12.7	f		18	52.8	2.8	Do.	30000	
		12.8	f		19	—	2.8	Do.	30000	
		2.5	f		20	54.6	2.7	y′ r B g	27000	
		2.6	f		20	—	2.9	y′ r	31000	
		5.8	f		20	52.7	2.7	w r g	27000	
		6.1	f		20	—	{3.6 3.3}	w *c* g / Do.	57000 46000	
	Mar. 27	9.4	f	W.	18	55.7	3.5	w *c* B g	53000	
		9.8	f		18	—	3.6	w r g	59000	
		11.0	f		18	62.8	2.8	w br B p	30000	
		11.5	f		19	—	2.9	Do.	31000	
		12.7	f		19	67.2	2.9	w br bg	31000	
		2.8	c′		20	68.5	2.8	y′ br bg	28000	
		5.8	c		21	—	2.7	w br B p	25000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture s.	Corona Colors.	Number n.	Remarks.
1903	Mar. 27	5.9	c		21	62.8	3.2	w r g	42000	
	Mar. 28	10.2	f	W.	21	51.8	2.0	cor	11000	
		10.4	f		21	—	2.0	w br B g	11000	
		12.8	f		22	58.3	2.3	w br B g	15500	
		1.0	f		22	—	2.8	y br B b	30000	
		2.6	f		23	59.3	2.6	w r|g	22000	
		3.3	f	N.W.	23	—	2.6	w′ r g	24000	
		5.7	f		23	47.0	2.2	cor	14500	
		5.9	f		23	—	2.2	w br B	13500	
	Mar. 29	10.1	f	N.W.	20	36.5	3.1	w r b g	38000	
		10.7	f		19	—	3.3	w *c* g	45000	
		1.2	f		20	42.0	2.7	w r g	27000	
		1.5	f		20	—	2.8	w br B g	28000	
		4.3	f		20	44.4	2.6	w br B	22000	
		4.4	f		20	—	2.7	y′ br bg	27000	
		5.0	f	N.	20	43.5	2.9	y br|bg	31000	
		6.6	f		20	51.0	2.8	w r g	28000	
		6.7	f		20	—	2.8	w br B p	28000	
	Mar. 30	9.9	c	S.E.	17	43.3	2.7	w br B p	27000	
		10.9	c		17	—	3.8	y′ r g	66000	
		11.1	c		17	44.5	3.7	y r bg	62000	
		11.5	c		17	—	3.7	w r g	62000	
		12.7	c		18	46.8	2.8	w br B p	28000	
		12.9	c		18	—	3.5	w r g	53000	
		1.1	c		18	—	3.5	w r g	53000	
		2.5	c		19	48.3	3.2	w br B	42000	
		2.7	c		19	—	3.4	w br g	49000	
		5.7	c		20	46.3	2.3	w br B g	16500	
		5.8	c		20	—	2.3	w br B g	15500	
	Mar. 31	9.4	c R′	N.	21	—	2.9	w br B r	31000	
		9.5	c		21	42.7	2.8	w c g	30000	
		12.9	c		21	46.6	2.8	y′ br|g	28000	
		1.0	c		21	—	2.7	Do.	27000	
		3.3	c	W.	21	53.3	2.7	w br	25000	
		4.0	c		21	—	2.7	w br|bg	25000	
		5.5	f′ (S)		22	—	2.3	w br B|p	15500	
		5.6	f		23	55.1	2.8	w br g	28000	
	Apr. 1	9.4	f	W.	19	52.7	2.0	cor	11000	
		9.5	f		19	—	2.8 2.4	w br B bg w br B	28000 18000	
		12.5	c		20	56.6	2.7	w br B	25000	
		12.6	c		20	—	2.2	w br|g	14500	
		3.7	f		22	56.2	2.8	w br B p	28000	
		3.8	f		—	—	3.5 2.8	w r g	53000 28000	
		7.7	f		22	49.0	2.8	w r g	28000	
		7.8	f		22	—	2.7	w r g	27000	
	Apr. 2	9.0	f	S.E.	19	46.5	2.8	w r g	28000	
		9.3	f		19	—	2.9	w br B p	31000	
		12.1	f		20	51.6	2.4	cor	17500	
		12.2	f		20	—	2.7	w br g	25000	
		12.8	f		20	—	2.5	w br B g	20000	

TABLE 1—*Continued.*

Year.	Date	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1903	Apr. 2	5.3	f	S.	22	47.6	2.7	w r g	27000	
		5.4	f		22	—	2.7	w r g	27000	
		5.5	f		—	—	2.8	w br B p	28000	
	Apr. 3	9.4	c R′	S.W.	21	57.7	2.5	w r B g	21000	
		10.2	c		21	—	2.7	w br B g	26000	
		10.4	c		21	—	2.7	w br B p	26000	
		10.6	c		21	—	2.8	w br	28000	
		12.5	c		22	62.3	2.6	w r B g	22000	
		12.6	c		22	—	2.8	w br B g	28000	
		3.8	c		23	60.5	2.7	y′ p B g	24000	
		4.2	c		23	—	2.7	Do.	24000	
		5.7	c		23	60.0	2.8	w or G	30000	
		6.0			24	—	2.7	Do.	27000	
	Apr. 4	10.2	c R′	S.W.	22	60.4	2.8	w|B p	28000	
		10.3	c		22	—	2.8	Do.	28000	
		12.0	c R	N.W.	23	60.1	2.9	w br diff.	31000	
		12.0	c		23	—	2.8	w br B p	28000	
		3.9	c		24	43.3	2.8	y r g	28000	
		4.0	c		23	—	2.8	y′ r g	28000	
		5.7	c		24	37.7	2.5	w br	20000	
		5.8	c		24	—	2.5	w br B g	20000	
	Apr. 5	9.6	f	N.W.	21	33.4	3.0	w br B gy r	37000	
		9.7	f		21	—	3.2	w *c*|g	44000	
		1.1	f		21	40.0	3.2	w *c* g	44000	
		1.4	f		21	—	3.1	w br B|p	38000	
		4.4	f		21	40.0	2.8	y′ r bg	30000	
		4.6	f	N.	21	—	3.8	y′ br b	68000	
		4.7	f		21	39.0	4.1	Do.	83000	
		5.1	f		21	—	2.7	y br B g	27000	
		5.6	f		21	—	3.2	w r B g	42000	
		6.3	f		22	37.1	3.7	g′ B p	27000	
		6.4	f		—	—	3.1	{ w r br g } { w br B g }	40000	
	Apr. 6	9.3	f	S.	21	37.0	3.4	w r B g	49000	
		9.5	f		20	—	2.8	w br B p	30000	
		11.4	f		20	42.0	2.9	w br bg	31000	
		11.5	f		20	—	2.9	w br B|p	33000	
		3.0	f		22	42.0	2.4	w r B g	19000	
		3.4	f		21	—	2.7	y′ r g	25000	
		3.7	c′		21	—	2.6	w r b g	24000	
		5.6	c		23	40.5	3.0	w y B g	35000	
	Apr. 7	10.8	c R	S.	22	—	2.9	w|B p	31000	
		12.4	c R		22	52.5	2.7	Do.	25000	
		12.5	R		22	—	2.7	Do.	27000	
		2.8	R		23	52.5	2.6	w r B g	24000	
		2.9	R		23	—	2.7	y′ r|g	25000	
		5.5	R		24	53.6	2.6	w r g	24000	
		5.7	R		24	—	2.6	w br B p	22000	
	Apr. 8	9.3	R	S.	23	51.7	2.4	w br B g′ r	17500	
		9.5	R		22	—	2.3	Do.	16500	
		11.8	R	E.	23	53.3	2.2	cor	13500	
		12.1	R		23	—	2.2	Do.	14500	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1903	Apr. 8	4.2	R	S.	24	54.5	3.2	w br B g	44000	
		4.3	R		24	—	2.8	w br B p	28000	
		4.4	R		24	—	2.7	Do.	27000	
	Apr. 9	9.1	f	W.	23	55.0	2.2	w br B g p|r	14500	
		9.4	f		22	—	2.6	y r|g	22000	
		9.6	f		22	—	2.6	y r g	23000	
		12.2	f		23	61.4	2.7	w br B p	25000	
		12.3	f		23	—	2.6	w r|g	24000	
		3.9	f		24	63.4	2.7	g br B p	25000	
		4.1	f		24	—	2.7	Do.	27000	
		5.4	f		24	61.1	2.7	Do.	27000	
		5.6	f		24	—	3.3 3.1	w br Do.	45000	
	Apr. 10	9.4	f′ R	N.	22	54.0	2.2	w br B|r	14500	
		9.6	f′		21	—	2.6	w r B g	22000	
		9.9	f′		21	—	2.6	Do.	22000	
		12.4	f′ (S)		22	58.1	2.9	w or bg	31000	
		12.5	f′ (S)		22	—	3.3	w r b g	45000	
		12.7	f′		22	—	2.8	g B p	28000	
		3.1	f′ (S)	N.W.	23	61.7	2.5	y′ br B|r	20000	
		3.4	f′ (S)		23	—	2.6	w br B	22000	
		5.8	f		23	57.7	2.2	cor	14500	
		5.9	f		23	—	2.5	cor	20000	
	Apr. 11	9.4	f	N.	21	52.4	2.8	w br B|p	28000	
		9.6	f		21	—	2.8	w|B|p	28000	
		12.1	f		22	57.2	2.8	w br	28000	
		12.2	f		22	—	3.3	w br bg	45000	
		12.5	f		22	—	2.8	w br B p	28000	
		2.8	f		22	59.4	2.2	w br B g r	14500	
		3.0	f	W.	22	—	2.5	y o|g	21000	
		5.4	f		23	56.7	2.2	cor	14500	
		5.6	f		23	—	2.6	w r g	24000	
	Apr. 12	9.8	f	N.	20	51.5	2.3	w br B g r	16500	
		10.3	f		20	—	2.8	g′ br B p	28000	
		10.8	f		20	—	3.3	w r B g r	47000	
		11.3	f		20	55.0	2.8	w|B p	30000	
		11.5	f		20	—	2.8	Do.	28000	
		1.0	f		22	—	2.4 2.8	w r B g w br B g	17500 28000	
		4.0	f		21	57.0	2.3	y′ r bg	16500	
		4.1	f		21	—	2.5	Do.	20000	
		6.0	f		22	54.3	2.4	cor	19000	
	Apr. 13	8.9	f	N.E.	20	49.8	2.7	w o B bg	25000	
		9.1	f		20	—	3.0	w br B p	37000	
		9.3	f		20	—	2.8	Do.	28000	
		12.0	f		20	54.6	2.6	w r|g	24000	
		12.1	f		20	—	2.6	w o|bg	24000	
		3.5	f		21	—	2.1	cor	12500	
		3.6	f		21	53.0	2.3	Do.	16500	
		5.8	f		22	46.5	2.0	Do.	10000	
		5.9	f		22	—	2.0	Do.	10000	
	Apr. 14	9.2	c	E.	20	44.7	2.1	w br B g p	11500	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1903	Apr. 14	9.4	c		19	—	2.5	w r B g	20000	
		9.7	c		19	—	2.2	cor	14500	
		9.9	c		19	45.8	2.3	cor	—	
		10.1	c		19	—	2.1	cor	—	$\delta p = 22$
		10.2	c		19	—	2.1	cor	—	
		12.3	c		20	46.4	2.1	cor	11500	
		12.4	c		20	—	2.2	w br B g p	14500	
		12.5	c		20	—	2.9	w br B	—	$\delta p = 9$
		12.6			—	—	1.8	cor	—	$\delta p = 22$
		3.5	c		21	46.2	2.3	cor	15500	
		3.6	c		21	—	2.2	cor	13500	
		6.0	c		21	43.9	2.0	cor	10000	
		6.1	c		21	—	2.0	cor	10000	
	Apr. 15	9.3	c	N.E.	21	—	1.7	cor	—	$\delta p = 22$
		9.4	R		19	43.7	2.1	cor	11500	
		9.5	R		19	—	1.8	cor	7000	
		9.8	R		19	—	1.7	cor	—	$\delta p = 22$
		12.1	R		20	44.5	2.1	cor	11600	
		12.2	R		20	—	2.0	cor	11000	
		3.7	R		21	44.7	1.8	cor	8000	
		4.2	R		21	—	1.9	cor	9000	
		5.9	R′		21	43.5	1.8	cor	8000	
		6.0	R′		21	—	2.1	cor	12500	
	Apr. 16	9.5	c	N.E.	19	42.0	2.1	cor	11500	
		9.7	c		18	—	2.1	w br B|p	12500	
		12.7	c		20	43.4	2.2	cor	13500	
		12.9	c		19	—	2.3	w br B|p	16500	
		6.3	c		21	40.5	2.2	cor	13500	
		6.4	c		21	—	2.2	cor	13500	
	Apr. 17	9.3	c	N.	20	42.1	2.5	cor	20000	
		9.6	c		20	—	2.4	w br B|p	19000	
		11.9	c		21	48.1	3.1	w br	38000	
		12.0	c		21	—	2.9	g′|B p	33000	
		12.4	c		21	—	2.7	w r B	—	$\delta p = 22$
		12.8	c		21	—	2.8	g′|B p	20000	
		3.4	c		21	45.8	2.3	cor	15500	
		3.7	c		21	—	2.6	y r|g	24000	
		4.1	c		21	—	2.6	y r|g	24000	
		5.8	c		22	45.7	2.7	y′ r|g	25000	
		6.0	c		—	—	2.6	Do.	24000	
	Apr. 18	9.0	f	W.	19	50.5	2.9	w br B bg	33000	
		9.2	f		19	—	3.2	w br B g r	42000	
		9.4	f		19	—	2.9	g′ br B|p	33000	
		9.7	f		19	—	3.4	w *c* g	49000	
		9.8	f		19	—	3.0	w′ br B|p	—	$\delta p = 22$
		9.9	f		19	—	3.8	w *c*|g	66000	
		10.0	f		19	53.7	3.3	w *c*|g	47000	
		12.1	f′		20	57.8	2.5	cor	21000	
		12.2	f′		20	—	2.7	w br B|p	25000	
		4.0	f		20	50.0	2.9	w br B|p	31000	
		4.1	f		20	—	3.3	w *c*|g	45000	
		4.4	f		20	—	2.8	w r|g	28000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture s.	Corona Colors.	Number n.	Remarks.
1903	Apr. 18	5.9	f		20	—	2.9	w br B p	31000	
		6.0	f		21	45.9	2.8	w r|g	28000	
		8.8	f		22	52.0	2.3	w br B g	15000	Night.
		9.3	f		21	—	2.4	Do.	17500	
		10.4	f		22	40.5	2.4	Do.	17500	
		10.5	f		22	—	2.7	w r|g	25000	
	Apr. 19	10.4	f	N.W.	22	49.8	2.2	cor	13500	
		10.6	f		21	—	2.5	cor	20000	
		12.1	f		21	53.1	2.4	cor	17500	
		12.5	f		21	—	2.6	w r|g	24000	
		3.7	f		21	56.7	2.6	y′ r|g	22000	
		3.8	f		21	—	2.6	Do.	22000	
		6.4	f		22	54.6	2.5	cor	20000	
		6.5	f		22	—	2.6	w br B g	23000	
	Apr. 20	8.9	f	W.	19	53.5	2.6	y′ r B g	22000	
		9.0	f		19	—	2.8	w r|bg	28000	
		11.4	f		20	60.2	2.7	y′ r|g	27000	
		11.6	f		20	—	2.7	g′ br B p	27000	
		3.5	f		22	64.5	2.5	cor	21000	
		3.8	f		21	—	2.8	y r B g	28000	
		5.1	f		22	63.2	2.8	w br B g	30000	
		5.3	f		22	—	2.8	w br B p	28000	
	Apr. 24	10.6	c′	W.	21	59.0	2.4	w r g	18000	
		11.4	c		20	—	3.2	w r|g	42000	
		11.5	c		20	59.7	2.8	g′ br B p	28000	
		12.4	c	S.	20	55.8	3.3	y r|g	47000	
		12.5	c		21	—	2.6	g′ br B p	24000	
		4.3	c′		22	55.0	2.5	y′ r|g	21000	
		4.6	c′		21	—	2.6	y r|g	24000	
		5.0	c′		21	—	2.7	w r|g	25000	
	Apr. 25	9.0	c	W.	20	56.7	2.7	cor	25000	
		9.1	c		20	—	2.6	w r B g	22000	
		12.4	c		21	60.5	2.8	w br|g	28000	
		12.5	c		21	—	2.7	w br b g	27000	
		12.7	c		21	—	2.8	g′ br B p	28000	
		4.2	c (S)	S.	22	59.7	2.5	cor	20000	
		—	f		22	—	2.5	cor	20000	
		5.6	f		22	—	2.5	cor	20000	
		5.8	f		22	58.6	2.8	cor	28000	
	Apr. 26	9.9	c′	N.E.	20	57.8	2.7	cor	18000	
		10.4	c′		20	—	2.4	cor	19000	
		12.4	c′		20	62.0	1.9	cor	8500	
		12.8	c′ (S)		20	—	2.0	cor	10000	
		1.1	c		20	—	2.2	cor	13000	
		6.2	c		21	54.8	2.1	cor	12000	
		6.5	c		21	—	2.1	cor	12000	
	Apr. 27	8.9	f	N.	19	50.4	2.4	cor	19000	
		9.1	f		19	—	2.4	cor	19000	
		12.3	f		20	61.4	2.1	cor	12500	
		12.4	f		20	—	2.4	cor	19000	
		12.6	f		20	—	2.4	cor	19000	
		3.6	f	N.E.	21	61.6	1.8	cor	8000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture s.	Corona Colors.	Number n.	Remarks.
1903	Apr. 27	3.8	f		21	—	1.8	cor	8000	
		5.8	f		22	—	1.8	cor	8000	
		6.0	f		22	58.5	2.1	cor	12500	
	Apr. 28	10.4	f	N.	20	65.8	2.1	cor	12500	
		10.5	f		20	—	2.4	cor	17500	
		10.8	f		20	—	2.7	w r b g	25000	
		11.7	f		20	68.4	2.8	g′ br B p	28000	
		12.5	f		20	70.0	2.3	cor	15500	
		12.6	f		20	—	2.6	cor	22000	
		5.1	f	S.	22	63.5	2.5	cor	20000	
		5.3	f		—	—	2.8	w br B g	28000	
		5.5	f		22	62.5	2.6	w r|g	24000	
		5.7	f		22	—	2.9	w o b	31000	
	Apr. 29	9.5	f	N.W.	20	—	2.7	w br B g	25000	
		9.8	f		20	75.2	2.7	w *c* B g	25000	
		12.1	f	W.	21	80.0	2.2	cor	14000	
		12.3	f		21	—	2.1	cor	13000	
		5.6	f		23	79.5	2.6	w *c* B g	22000	
		5.8	f		23	—	2.6	Do.	23000	
	Apr. 30	9.4	f	S.	22	68.5	2.2	cor	14000	
		9.5	f		22	—	2.6	w *c* B g	22000	
		9.8	f		22	—	2.4	w *c*|g	18000	
		12.4	f		23	72.7	2.2	cor	14000	
		12.5	f		23	—	2.2	cor	14000	
		3.7	f		24	74.5	2.6	cor|g	24000	
		3.9	f		23	—	2.6	w r|g	24000	
		5.5	f		24	65.5	2.4	w r|g	18000	
		5.6	f		24	—	2.8	w r|g	28000	
		5.8				—	—	Do.	28000	
	May 1	9.2	f′	W.	21	49.5	2.2	cor	14000	
		9.4	c		21	—	2.5	w *c* B g	20000	
		12.2	f′ (S)		21	56.6	2.5	w r b g	20000	
		12.5	f′		21	—	2.5	w br B g	21000	
		4.6	f	N.W.	22	55.2	2.2	cor	14000	
		4.7	f		22	—	2.5	w *c*|g	21000	
		6.0	f		22	52.8	2.1	cor	13000	
		6.1	f		22	—	2.3	cor	17000	
	May 2	9.3	f	E.	20	46.8	1.9	cor	8500	
		9.4	f		20	—	2.3	cor	16000	
		12.0	f		20	51.0	2.1	cor	12000	
		12.3	f		20	—	2.3	cor	16000	
		3.2	f		20	53.2	2.5	cor	20000	Clear air after
		3.3	f		20	—	2.3	cor	16000	western bliz-
		5.5	f		20	49.8	1.8	cor	7000	zard.
		5.6	f		20	—	1.8	cor	7000	
	May 3	9.9	c	S.W.	19	52.9	2.5	cor	20000	
		10.1	c		19	—	2.7	cor	25000	
		12.4	c		19	57.7	2.7	cor w r|g	25000	
		12.8	c		19	—	2.7	g br B p	27000	
		6.3	c	S.	19	54.0	2.1	cor	13000	
		6.4	c		19	—	2.3	cor	16000	
	May 4	9.0	c R′	N.	18	51.8	2.2	cor	14000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1903	May 4	9.1	c		18	—	2.8	cor	28000	
		9.6	c		18	—	2.6	cor	24000	
		12.1	c		19	55.7	2.6	w *c* B g	22000	
		12.4	c		19	—	2.7	w r b g	25000	
		6.1	c R′		21	53.3	2.5	cor	20000	
		6.2	c		21	—	2.7	cor	27000	
	May 5	9.0	c	N.	19	52.5	2.0	cor	10000	
		9.4	c		19	—	2.5	cor	20000	
		12.4	c		20	59.0	2.4	w *c*|g	19000	
		12.6	c		—	—	2.7	w br B g	23000	
		5.8	c		22	52.9	2.2	cor	14000	
		6.0	c		22	—	2.7	—	25000	
	May 6	9.3	c	N.	20	52.0	2.2	cor	14000	
		9.4	c		20	—	2.1	cor	12000	
		12.1	c		21	61.2	2.1	cor	12000	
		12.5	c		21	—	2.6	cor	23000	
		5.4	f′		22	59.5	2.0	cor	10000	
		6.0	f′		22	—	2.2	cor	14000	
	May 7	9.4	f	E.	20	58.8	2.7	w br B	27000	
		9.5	f	S.	20	—	2.8	w br|g	30000	
		12.4	f		20	65.5	2.7	w br B	25000	
		12.4	f		20	—	2.8	w br B g	28000	
		4.5	c		20	57.2	2.8	w br|g	28000	
		4.6	c		20	—	2.8	Do.	28000	
	May 8	9.6	f	N.W.	19	65.0	2.4	w br B|r	18000	
		9.7	f		20	—	2.2	cor	14000	
		12.4	f		21	72.2	2.4	cor	19000	
		12.8	f		20	—	2.2	cor	14000	
		5.6	f	S.E.	22	65.8	2.2	cor	14000	
		5.8	f		22	—	2.5	cor	21000	
	May 9	9.0	f	N.E.	20	70.2	2.2	cor	14000	
		9.3	f		20	—	2.2	cor	14000	
		12.4	f		21	71.7	1.7	cor	6000	
		12.7	f		21	—	1.7	cor	6000	
		3.4	f		22	70.3	1.8	cor	7000	
		3.7	f		22	—	1.7	cor	6500	
		5.7	f		22	67.2	1.6	cor	5000	
		5.8	f		22	—	1.8	cor	8000	
	May 10	10.1	f	S.W.	21	—	2.6	cor	22000	
		10.3	f		21	62.5	2.8	w br|g	28000	
		12.2	f		21	66.1	2.7	w br	25000	
		12.4	f		21	—	2.4	cor	18000	
		6.2	f		21	59.3	2.0	cor	11000	
		6.3	f		21	—	2.1	cor	13000	
	May 11	9.1	f	S.	19	64.4	2.9	g′ br B|p	31000	
		9.5	f		19	—	3.3	w *c* B	45000	
		11.9	f		20	70.0	2.9	w br B p	33000	
		12.3	f		20	—	2.9	w br B p	33000	
		5.7	f		21	61.5	2.7	w r B g	25000	
		5.8	f		21	—	2.8	w o|g	28000	
	May 12	9.1	f	S.	19	63.4	2.8	g′ br B p	30000	
		9.2	f		19	—	3.3	w r|g	45000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture s.	Corona Colors.	Number n.	Remarks.
1903	May 12	12.2	f		20	72.3	3.1	w br B p	38000	
		12.4	f		20	—	3.0	w *c* B g	35000	
		12.9	f		20	—	2.8	g′|B p	28000	
		5.0	f		21	64.4	2.4	cor	18000	
		5.4	f		21	—	2.6	w r|g	22000	
	May 13	9.4	f		19	62.9	2.8	w r B g	30000	
		9.5	f		19	—	2.8	Do.	28000	
		12.1	f		20	67.1	2.6	w *c* B g	22000	
		12.5	f		20	—	3.0	w br B g	35000	
		5.8	f		22	63.6	2.8	w r|g	28000	
		6.0	f		22	—	2.5	cor	21000	
	May 14	9.2	f	S.W.	20	70.1	2.9	w br B g	31000	
		9.5	f		20	—	2.7	w br B p	25000	
		3.2	f		22	78.5	2.3	cor	15000	
		3.4	f		22	—	2.3	w br B|p	16000	
		5.3	f		23	73.4	2.6	w r|g	23000	
		5.4	f		23	—	2.6	Do.	22000	
	May 15	10.9	f	N.W.	20	72.8	2.1	cor	14000	
		11.7	f		20	—	2.2	cor	14000	
		12.5	f		20	75.2	1.9	cor	8500	
		12.9	f		20	—	2.1	cor	12000	
		4.5	f		22	—	2.2	cor	14000	
		4.9	f		22	70.7	2.3	cor	15000	
		5.0	f		22	—	2.1	cor	—	$\delta p = 22$
		5.8	f		—	—	2.3	cor	16000	
	May 16	10.8	f	N.E.	20	66.0	1.7	cor	6500	
		10.9	f		20	—	2.0	cor	10000	
		11.8	f		20	68.5	1.8	cor	7000	
		12.1	f		20	—	2.0	cor	10000	
		3.9	f		22	69.4	2.2	cor	15000	
		4.0			22	—	2.5	cor	20000	
		5.8	f		22	63.8	1.8	cor	7000	
		5.9	f		22	—	1.8	cor	7000	
	May 17	3.3	f	S.W.	20	82.0	1.8	cor	7000	
		3.5	f		20	—	2.0	cor	11000	
		3.8	f		20	—	1.8	cor	7000	
		3.9	f		20	—	1.5	cor	—	$\delta p = 22$
		4.5	f		20	—	1.7	cor	—	$\delta p = 22$
	May 18	9.0	f	W.	21	78.0	2.6	w r B g r	24000	
		9.2	f		20	—	2.7	w r|g	26000	
		9.5	f		20	—	2.3	cor	17000	
		12.2	f	N.	22	86.0	2.0	cor	10000	
		12.3	f		22	—	2.0	cor	10000	
		12.4	f		22	—	1.9	cor	8500	
		4.6	f	N.W.	24	87.0	1.8	cor	8000	
		4.8	f		24	—	1.6	cor	5000	
		5.7	f		25	82	2.4	cor	18000	
		5.8	f		25	—	2.5	cor	20000	
	May 19	11.9	f	N.W.	25	89	2.3	cor	16000	
		12.4	f		25	—	2.1	cor	12000	
		12.6	f		25	90	2.0	cor	10000	
		12.8	f		25	—	1.6	cor	5500	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture s.	Corona Colors.	Number n.	Remarks.
1903	May 19	2.0	c		25	—	2.2	cor	14000	
		2.8	c		25	—	2.0	cor	11000	Storm coming.
		3.0	c		25	—	1.8	cor	7000	Thunder.
		3.1	c		25	84	1.8	cor	7000	
		3.8	c		25	—	2.4	cor	18000	
		4.0	c R		25	78	1.8	cor	7000	Hail.
		4.3	f′(S)		25	76	2.0	cor	11000	
		5.6	f′		25	76	2.3	w br B|p	15500	
		5.7	f′		25	—	2.1	cor	11500	
	May 20	9.4	f	N.W.	23	78	—	cor	—	
		9.5	f		23	—	2.7	w br	25000	
		9.9	f	S.	23	—	2.5	w r	20000	
		10.0	f′		23	—	2.8	w r|g	28000	
		12.3	c		24	80	2.2	cor	14500	
		12.4	f′		24	—	2.2	cor	14500	
		3.1	f		26	82	2.3	cor	15500	
		3.4	f		26	—	2.5	cor	20000	Thunder.
		5.7	c R		27	76	2.9	w r|g	31000	
		5.9	c R		27	—	2.6	w r|g	22000	
	May 21	9.7	f	N.W.	24	79	—	—	—	
		9.0	f		24	—	2.1	cor	11500	
		12.5	f		25	82	2.0	cor	11000	
		12.6	f		25	—	2.4	cor	17500	
		12.8	f		25	—	2.2	g br B|p	14500	
		3.0	f		26	80	2.5	w br	20000	
		3.1	f		26	—	2.4	w br	17500	
		4.8	f		26	76	2.4	cor	17500	
		4.9	f		26	—	2.6	w r|g	22000	
	May 22	9.3	f	W.	24	73	2.6	w r|g	23000	
		9.9	f		24	—	2.3	cor	16500	
		12.0	f		25	83	2.2	cor	13500	
		12.2	f		25	—	2.5	cor	20000	
		4.7	f		28	82	2.0	cor	10000	
		4.9	f		27	—	2.1	cor	11500	
		5.9	f		28	80	2.1	cor	11500	
		6.0	f		28	—	2.1	cor	11500	
	May 23	9.2	f	N.W.	22	64	lost	—	—	
		9.6	f		21	—	2.9	g′ B p	31000	
		9.9	f		21	—	2.7	g′ br B p	25000	
		11.0	f		21	69	2.9	y′ br b	31000	
		12.4	f		22	69	2.6	w r|g	22000	
		12.9	f		22	—	2.4	w br	19000	
		2.8	f		23	69	2.4	—	19000	
		3.3	f		23	—	2.8	w r|g	28000	
		5.8	f		23	65	2.2	cor	13500	
		5.9	f		23	—	2.2	cor	13500	
	May 24	9.7	c	N. E.	22	57	1.7	cor	6000	
		10.1	f′		22	—	2.0	cor	10000	
		12.3	f		22	62	2.0	cor	10000	
		12.5	f		32	—	2.1	w r g	11500	
		6.0	f		21	56	2.0	cor	10000	
		6.1	f		21	—	2.3	cor	15500	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture s.	Corona Colors.	Number n.	Remarks.
1903	May 25	9.3	f	N.W.	20	64	2.7	w r|g	27000	
		9.5	f	N.E.	19	—	2.7	w o b	26000	
		12.2	f		21	66	2.1	cor	11500	
		12.6	f		20	—	2.1	cor	11500	
		5.6	f		22	59	2.4	w r B p	17500	
		5.7	f		22	—	2.4	Do.	17500	
	May 26	9.1	f	S.	19	59	2.1	cor	11600	
		9.4	f		19	—	2.6	w r|g	24000	
		10.2	f		19	—	2.6	Do.	24000	
		12.1	f		20	61	2.2	cor	13500	
		12.2	f		20	—	2.3	w br B p	15500	
		12.4	f		20	—	2.2	cor	13500	
		3.4	f		20	61	2.2	cor	13500	
		3.7	f		20	—	2.3	cor	16500	
		5.3	f		21	—	2.5	cor	21000	
		5.6	f		20	58	2.5	cor	20000	
	May 27	9.2	c	S.	20	64	2.7	w r|g	25000	
		9.4	c		25	—	2.9	w r B	31000	
		10.0	c		20	—	2.6	cor	22000	
		12.2	c		21	72	2.6	cor	22000	
		12.3	c		21	—	3.0	w br B p	35000	
		12.5	c		21	—	2.7	w r|g	27000	
		3.6	c		21	70	2.3	w br B p	15500	
		3.7	c		21	—	—	—	—	
		5.8	f′		22	68	2.3	w br B|p	15500	
		6.0	f		22	—	2.3	Do.	16500	
	May 28	9.6	c′	S. W.	21	72	?2.6	g′ br B p	?22000	
		9.8	c′		21	—	?2.6	Do.	?22000	
		11.7	c R′		22	68	2.8	y′ r|g	28000	
		12.0	c		22	—	3.0	g′ br B p	35000	
		3.3	c		23	69	2.7	w r|g	25000	
		3.5	c		23	—	2.7	w r|g	26000	
	May 29	9.5	f	S.	21	71	2.7	w r|g	25000	
		10.0	f		20	—	2.8	y′ or bg	30000	
		12.2	f		22	76	2.4	cor	17500	
		12.4	f		22	—	2.6	w r|g	22000	
		4.7	f		24	71	2.3	w br B|p	15500	
		5.8	f		23	71	2.5	w br B	20000	
		6.0	f		23	—	2.7	w r|g	25000	
	May 30	9.8	c R′	S.	20	56	2.0	cor	11000	Rain at night.
		10.1	c		21	—	2.0	cor	10000	
		10.8	c		21	—	2.0	cor	10000	
		12.4	c		21	60	1.8	cor	7000	
		12.5	f′		20	—	1.8	cor	7000	
		5.8	f		23	61	2.2	cor	13500	
		6.0	f		23	—	2.2	cor	13500	
	May 31	12.8	f	N.	20	66	1.7	cor	6000	
		1.4	f		20	—	2.0	cor	10000	
		6.4	f		20	60	1.7	cor	6000	
		6.4	f		20	60	1.7	cor	6000	
		6.5	f		20	—	1.9	cor	8500	
	June 1	12.5	f	N. E.	19	68	2.0	cor	11000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture s.	Corona Colors.	Number n.	Remarks.
1903	June 1	12.7	f	S.	19	—	2.3	cor	16500	
		4.6	f		21	65	2.2	g′ br B p	13500	Maine forest fires.
		5.4	f		21	—	2.6	w r|g	22000	
		5.6	f		21	64	2.6	w br B g r	22000	
	June 2	9.4	f	N. E.	19	—	lost	small cor	—	
		9.7	f		19	67	1.7	cor	6000	
		12.2	f		20	69	2.5	w br	20000	
		12.4	f		20	—	2.8	w r|g	28000	
		5.7	f	S.	22	65	2.7	w r|g	25000	
		6.0	f		22	—	2.7	w r|g	26000	
		7.6	f		22	61	2.3	cor	15500	
		7.8	f		22	—	2.3	cor	15500	Night.
		10.2	f		21	56	2.4	w r g	17500	New revoluble
	June 3	9.3	f	W.	20	72	2.0	cor	11000	mounting.
		9.4	f		20	—	2.1	cor	11500	
		12.2	f		24	81	1.9	cor	9000	
		12.6	f		24	—	2.0	cor	10000	
		3.1	f		25	83	2.0	cor	10000	
		3.3	f		—	—	2.0	cor	10000	
		5.7	f		25	80	2.5	cor	20000	
		5.8	f		25	—	2.9	w r|g	31000	Red moon.
	June 4	9.0	fog	N.	23.1	62	3.0	w r|g	35000	Red sun.
		9.5	"		23.1	—	2.9	w br|g	31000	
		9.8	red sun		23.1	62	2.8	Do.	30000	
		12.0			24.1	66	2.5	w br	21000	
		12.2	fog, yel.		21.1	—	2.4	w br B p	17500	
		2.4	red sun		22.1	67	2.4	w br B p	19000	Forest fires on
		2.5	fog red sun		22.1	—	2.5	Do.	20000	Cape Cod.
		2.6	fog red sun		22.1	—	2.4	Do.	17500	
		5.9	fog		23.1	63	2.3	w br B|p	16500	
		6.0	fog		23.1	—	2.3	Do.	16500	
	June 5	9.5	haze, sun yel.		19.1	60	3.0	w|B p	35000	
		9.7	Do.	N. E.	18.1	—	2.6	cor	22000	Forest fires on
		9.7	Do.		18.1	—	2.5	cor	20000	Cape Cod.
		12.1	Do.	S.	20.1	68	2.0	cor	10000	
		12.3	Do.		20.1	—	1.8	cor	7000	
		3.7	Do.		22.1	68	2.2	cor	13500	
		3.8	Do.		22.1	—	2.2	cor	13500	
		5.5	Do.		21.1	65	2.4	cor	17500	
		5.7	haze sun ruby		22.1	—	2.5	cor	20000	
	June 6	9.4	haze	S.W.	19.1	64	2.8	g br B p	28000	
		9.5	haze		19.1	—	2.8	w r|g	28000	
		12.6	c		22.1	68	2.2	cor	13500	
		12.8	c		22.1	—	2.5	cor	20000	
		3.1	c		22.1	71	2.4	cor	17500	
		3.7	c		22.1	—	2.6	cor	22000	
		3.9	c		22.1	—	2.4	cor	17500	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1903	June 6	5.8	c		22.1	69	2.3	w br B p	16500	
		5.9	c		22.1	—	2.3	Do.	15100	
	June 7	10.3	R′	S.	20.1	65	2.7	w r g	25000	
		10.8	R′		20.1	—	2.0		10000	
		12.0	c R′		21.1	66	2.2	cor	13500	
		12.1	c		21.1	—	2.0	cor	11000	
		4.6	f′		21.1	68	2.0	cor	10000	
		4.8	f		21.1	—	2.1	cor	11500	
		6.1	f		21.1	66	2.1	cor	11500	New axis and support.
		6.3	f		21.1	—	1.9	cor	8500	
	June 8	10.4	c	S.	20.1	72	2.1	cor	11500	
		11.1	c		21.1	—	2.5	y′ br B g	21000	
		11.4	c		21.1	73	2.3	Do.	15500	
		12.5	c		22.1	75	2.0	cor	11000	
		12.8	c		21.1	—	2.4	w o B g r	17500	
		2.5	c		22.1	70	2.1	cor	11500	
		2.7	c		22.1	—	1.9	cor	8500	
		3.1	c		22.1	—	2.2	cor	13500	
		6.8	R		23.1	67	2.1	cor	11500	
		6.9	R		23.1	—	2.2	cor	13500	
	June 9	9.0	c wet	S.	21.1	68	2.3	cor	15500	
		9.2	c		21.1	—	2.1	cor	11500	
		12.4	c		22.1	74	2.7	y′ r B g	26000	
		12.5	c		22.1	—	2.7	Do.	26000	
		3.1	c		23.1	72	2.1	y′ r B g	11500	
		3.3	c		23.1	—	2.3	w br B|r	15500	
		5.5	c		23.1	67	2.3	cor	15500	
		5.6	c		—	—	2.2	cor	13500	
	June 10	9.3	c	S.	21.1	70	1.4	cor. small.	3000	
		9.5	c		21.1	—	1.5	Do.	4500	
		12.0	c		22.1	75	1.7	Do.	6500	
		12.2	c		22.1	—	1.8	Do.	7000	
		3.4	c		23.1	71	2.0	cor	11000	
		3.6	c		23.1	—	2.3	w o B|r	15500	
		5.8	c		24.1	67	1.8	cor	8000	
		6.0	c		24.1	—	2.0	cor	11000	
		9.5	c R		22.1	70	1.8	cor	8000	
	June 11	9.6	R	E.	22.1	—	1.7	cor	6000	
		12.2	c		22.1	70	1.9	cor	8500	
		12.3	c		22.1	—	1.9	cor	8500	
		4.0	c		23.1	75	1.6	cor. small	5000	
		4.1	c		23.1	—	1.6	cor. small	5000	
		6.1	c		24.1	67	1.7	cor	6000	
		6.2	c		24.1	—	1.7	cor	6000	
	June 12	9.2	R	E.	22.1	69	1.3	cor	2500	
		9.4	R		22.1	—	1.3	cor	2500	
		12.7	R		23.1	70	1.4	cor	3500	Violent wind storm.
		12.8	R		23.1	—	1.6	cor	5000	
		4.2	c R′		23.1	66	1.8	cor	7000	
		4.8	c	S.	23.1	—	1.7	cor	7000	
		6.0	c		24.1	65	1.7	cor	6500	
		6.1	c		24.1	—	1.7	cor	6000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1903	June 13	9.6	R	S.	21.1	68	2.2	y′ br B g p	14500	
		9.9	c		21.1	—	2.6	w br B g r	22000	
		10.4	c		21.1	—	2.9	w br B p	31000	
		11.9	c		22.1	72	2.2	w br	13500	
		12.2	f′ (S)		22.1	—	2.2	w br	13500	
		4.6	f (S)		23.1	70	2.2	y o|g	13500	
		4.8	f		23.1	—	2.4	w br b|p	17500	
		5.7	f		23.1	68	2.4	w br B g′ b	17500	
		6.0	f		23.1	—	2.1	w r b g	11500	
	June 14	10.0	f	S.	21.1	68	1.8	cor	8000	
		1.1	f		22.1	70	1.9	cor	8500	
		1.2	f		22.1	—	1.8	cor	8000	
		4.7	f		21.1	69	1.3	cor	2500	
		4.8	f		21.1	—	1.3	cor	2500	
		6.3	f		22.1	66	1.7	cor	6000	
		6.4	f		22.1	—	1.7	cor	6000	
	June 15	10.1	c R	N.	19.1	58	2.1	cor	12500	
		10.4	R		19.1	—	2.1	cor	12500	
		11.5	c R′		18.1	58	2.1	cor	12500	
		11.7	c		18.1	—	2.1	cor	12500	
		4.7	R′		22.1	56	1.8	cor	7000	
		4.8	c		22.1	—	1.7	cor	6000	
		6.3	R′		22.1	55	1.6	cor	5500	
		6.5	R′		22.1	—	1.6	cor	5500	
	June 16	9.5	R′	N.	19.1	52	1.7	cor	6000	
		9.7	R′		19.1	—	1.8	cor	8000	
		12.3	c		18.1	55	1.9	cor	8500	
		12.4	c		18.1	—	1.9	cor	8500	
		6.5	c		17.1	55	1.8	cor	7000	
	June 17	9.1	f	E.	17.1	64	3.3	w p|g	45000	
		9.3	f		17.1	—	3.4	w p|g g′ br	49000	
		4.4	f′ (S)		18.1	—	2.2	cor	13500	
		4.4	f′		18.1	65	2.1	cor	11500	
	June 18	9.7	c	E.	17.1	60	2.3	w br B g|r	15500	
		10.1	c		16.1	—	2.4	cor	19000	
		11.8	c		17.1	65	2.3	cor	15500	
		12.0	c		17.1	—	2.3	cor	15500	
		4.4	c	S.	18.1	62	2.5	w r b g′ r	20000	
		4.8	c		18.1	—	2.5	w r B g′bg	21000	
		6.0	c		19.1	59	2.3	cor	16500	
		6.2	c		19.1	—	2.4	cor	17500	
	June 19	9.6	c	S.	17.1	62	2.4	cor	17500	
		9.8	c		17.1	—	2.4	cor	17500	
		12.8	c		18.1	63	2.5	w br B g′r	21000	
		12.9	c		—	—	2.7	w *c*|g	25000	Fire on campus.
		5.8	c		19.1	61	2.0	cor	10000	
		6.0	c		19.1	—	2.1	cor	11500	
	June 20	9.8	c	S.	17.1	65	2.2	cor	13500	
		9.9	c		17.1	—	2.2	w o B|p	14500	
		12.8	c		19.1	69	2.3	w br B|p	16500	
		12.9	c		19.1	—	2.5	w br B g ′r	21000	
		3.2	c		19.1	64	1.9	cor	8500	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture s.	Corona Colors.	Number n.	Remarks.
1903	June 20	5.8	c		19.1	63	2.5	cor	20000	
		6.0	c		19.1	—	2.4	w br B|p	19000	
	June 21	10.5	R	E.	18.1	62	1.8	cor	7000	
		10.6	R		18.1	—	1.7	cor	6000	
		12.2	c R′		18.1	62	1.5	cor	4000	
		12.3	c R′		18.1	—	1.5	cor	4000	
		4.3	c R		18.1	60	1.8	cor	7000	
		4.8	R		18.1	—	1.8	cor	7000	
		6.4	R		19.1	58	1.8	cor	7000	
		6.6	R		19.1	—	1.8	cor	7000	
	June 22	9.5	c R′	N. E.	17.1	57	1.7	cor	6000	
		9.7	c		17.1	—	1.7	cor	6500	
		12.6	c		18.1	59	1.8	cor	7000	
		2.8	c		19.1	60	1.9	cor	9000	
		5.6	c		19.1	59	2.8	w|B p	30000	Fire on campus.
		5.9	c		19.1	—	3.6	w r g	57000	" " "
	June 23	9.6	c	E.	17.1	59	1.6	cor	5500	
		9.8	c		17.1	—	4.1	g B p	100000	Fire on campus.
		12.5	c		18.1	58	1.8	cor	7000	
		1.0	c		18.1	—	1.8	cor	7000	
		5.8	R		19.1	54	2.0	cor	10000	
		6.0	R		19.1	—	1.9	cor	8500	
	June 24	9.8	c	N. E.	17.1	55	1.6	cor	5500	
		9.9	c		17.1	—	1.8	cor	7000	
		1.3	c R′		18.1	57	1.6	cor	5500	
		5.8	c		19.1	54	1.8	cor	7000	
		6.0	c		19.1	—	1.9	cor	8500	
	June 25	9.6	c	N.	16.1	57	2.1	cor	12500	
		10.7	c		16.1	—	2.0	cor	11000	
		12.8	c		17.1	59	2.3	w o B g′r	15500	
		12.9	c		17.1	—	2.5	w br B g r	20000	
		3.7	c		18.1	60	2.1	cor	11500	
		3.8	c		18.1	—	2.1	w o b g	11500	
		5.9	c R′		18.1	59	2.3	w br B g	16500	
		6.0	c		18.1	—	2.3	Do.	15500	
	June 26	9.5	f (S)		16.1	70	2.4	y′ br B g′ r	17500	
		9.8	f	W.	17.1	—	2.3	w br B g r	15500	
		12.2	f		18.1	74	2.8	w or|g	28000	
		12.4	f (S)		18.1	—	2.8	w or b g r	28000	Fire on campus.
		4.3	f		20.1	76	2.5	w br B p	21000	
		6.0	f		20.1	73	2.3	w br B g r	15500	
	June 27	9.7	f	W.	18.1	75	1.8	cor	7000	
		9.8	f		18.1	—	2.4	w br B g ′r	17500	
		12.0	f		19.1	81	2.5	Do.	21000	Fire on campus.
		4.4	f		20.1	80	2.7	w br b g′ r	25000	
		6.4	f		21.1	75	2.3	w br|g	15500	
	June 28	10.3	f ′(S)	N.	19.1	72	3.0	y br|g	35000	
		10.8	f		19.1	—	2.8	Do.	30000	
		1.3	f		20.1	75	2.3	w br B g′p	16500	
		1.4	f		20.1	75	2.3	w br B g′p	16500	
		5.0	f	S.	20.1	69	2.2	w br|g	14500	
		6.8	f		20.1	65	1.9	cor	8500	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1903	June 29	9.6	f′ (S)		18.1	70	1.8	w br B|g	8000	
		11.9	f′	E.	20.1	72	1.7	cor	7000	
		3.4	c		—	68	1.7	cor	7000	
		5.8	c R		21.1	61	2.2	w br B g r	13500	
							2.2	w o|g		
	June 30	9.6	f′	N.	19.1	68	2.9	g′|b′p	31000	
		9.8	f′		19.1	—	2.9	w br b g r	21000	Runs to w r g for large *d*.
		10.0	f′		19.1	—	2.9	g′ b p	31000	Fire on campus.
		12.2	f′		20.1	72	2.9	w r|g	31000	
		2.5	f		21.1	75	2.6	w br B	22000	
		5.3	f	S.	22.1	71	2.7	w r|g	25000	
		5.5	f		22.1	—	2.8	Do.	28000	
	July 1	9.3	R	S.	20.1	72	3.1	g′ b p	38000	
		10.5	f′		21.1	77	3.1	g′ br B|p	38000	
		12.7	f′ (S)		22.1	85	2.4	w br B|r	17500	
		2.3	f		22.1	87	2.4	Do.	17500	
		4.7	f′		23.1	—	2.9	w o|g	31400	
		5.5	f′ (S)		24.1	87	2.9	w B p	31400	
							2.9	w r g		
	July 2	9.5	f	W.	22.1	87	3.0	g′ B p	35000	
		9.7	f (S)		22.1	—	3.0	Do.	35000	
		11.3	f		23.1	90	2.4	w br B g|r	19000	
		1.8	f		24.1	92	2.5	w br B|r	20000	
		4.3	f		25.1	90	2.7	w r g	26000	
		5.5	f		25.1	89	2.4	cor	17500	
	July 3	9.7	f	W.	23.1	82	2.7	w r g	26000	
		10.7	f		23.1	82	2.3	w br b g	15500	
		1.0	f		24.1	84	2.3	cor	15500	
		2.8	f		25.1	85	2.3	w br B g′r	16500	
		4.8	f		26.1	84	2.3	w br|g	15500	
		5.9	f		26.1	82	2.7	w r g	26000	
							2.8	w o g		
	July 4	9.8	f	N.	23.1	74	2.5	w br B g′r	20000	
		11.5	f		24.1	78	2.2	cor	13500	
		12.6	f		25.1	79	2.0	cor	10000	
		3.0	f		25.1	81	2.2	w br|g	13500	
		5.4	f		—	71	2.0	cor	10000	
	July 5	9.4	f′ (S)	S.W.	23.1	74	2.2	w br b g r	13500	
		11.8	f′		24.1	78	2.2	w y|g	14500	
		5.1	f		24.1	77	1.7	cor	6000	
		6.4	f		24.1	73	1.7	cor	6500	
	July 6	9.3	R	S. W.	22.1	66	2.6	w br B g r	22000	
		10.3	R		23.1	66	2.9	w B p	31000	
		12.0	R′		23.1	68	2.5	w br B|r	20000	
		6.0	f		25.1	71	2.3	w o|g	15500	
	July 7	9.5	f	N.W.	23.1	79	2.7	w r g	25000	
		11.2	f		24.1	83	2.5	w br B g r	20000	
		1.1	f		24.1	85	2.1	cor	14500	
		3.8	f		25.1	85	2.3	w br B g′r	15500	
		5.5	f		25.1	84	2.1	w br|g	14500	
	July 8	9.8	f	W.	23.1	83	2.2	cor	13500	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1903	July 8	11.9	f		—	87	2.2	w br bg r	13500	
		3.4	f		26.1	89	2.4	w br B|r	17500	
		5.7	f		26.1	86	{ 2.6 / 2.7 }	{ w r b g / w r|g }	22000	
	July 9	9.7	f	N.W.	24.1	85	1.9	cor	8500	
		12.1	f		26.1	91	1.9	cor	9000	{ Low on hot, clear day.
		3.0	f		27.1	93	1.5	cor	4500	
		5.8	f		27.1	91	2.1	cor	12500	
		6.0	f		28.1	—	2.1	w br|g	12500	
	July 10	9.2	f (S)	S.	—	88	2.9	g′ Bp	31000	Old apparatus.
		9.4	f		26.1	—	2.9	g′(br) B p	31000	" "
		9.9	f		27.1	90	3.0	Do.	35000	New apparatus.
		10.5	f		27.1	—	2.8	w r|g	28000	
		11.3	f		27.1	93	2.8	w br B g p	28000	
		12.4	f′		27.1	94	2.8	w r|g	28000	
		12.8	f′		27.1	—	2.8	g′ (br) B|p	28000	
		3.6	f		28.1	92	2.4	w br B|g r	17500	
		5.1	c		28.1	87	2.8	w r|g	28000	Coming storm.
		5.3	c R′		28.1	—	2.8	g|B p	30000	Blown over.
	July 11	9.5	f		26.1	84	3.6	w r|g	57000	Empty of water.
		9.7	f	W.	25.1	—	3.0	w br B|p	35000	Water put in.
		9.9	f		25.1	—	3.7	w r|g	61500	
		10.4	f		26.1	—	2.8	g′|B|p	30000	
		10.9	f		26.1	88	2.4	w br B g p	17500	Old apparatus.
	July 13	9.6	c R′	W.	26.1	74	2.3	w br B g′ p	16500	
		9.8	R′		26.1	—	2.3	Do.	16500	
		12.9	c R		27.1	74	2.3	w br B|p	16500	
		3.8	c		27.1	73	2.0	cor	11000	
		5.7	c		27.1	73	3.0	w br B	35000	
		5.8	c		27.1	—	2.8	w r|g	28000	
	July 14	9.4	f′ (S)		25.1	76	2.4	cor	17500	
		9.8	f′	W.	24.1	—	2.4	w br B g′ r	17500	
		11.2	f		25.1	77	2.7	w r|g	25000	
		12.5	f		26.1	78	2.7	w br B|p	25000	
		2.9	f		26.1	79	2.4	cor	17500	
		4.3	f		26.1	77	2.3	w br B g r	15500	
		5.7	f		26.1	74	{ 2.8 / 2.8 }	{ w r|g / w r g }	28000	
	July 15	9.8	f	W.	23.1	72	2.2	w br B r	14500	Rain during night.
		10.6	f		23.1	74	2.4	w br B g r	17500	
		11.8	f		24.1	74	2.8	w r|g	28000	
		4.3	f′ R′		25.1	69	2.2	w o b g r	13500	
		5.7	f		25.1	68	2.3	w|B|p	16500	
	July 16	9.3	f	W.	22.1	70	2.5	w br B|r	20000	
		12.3	f		23.1	74	2.4	Do.	19000	
		5.6	f		23.1	72	2.2	w br B|r	14500	
	July 17	11.4	f	W.		79	2.3	cor	15500	
		12.2	f		22.1	78	2.2	cor	14500	
		5.6	f		22.1	79	2.5	cor	20000	
	July 18	10.9	f′	S. W.	22.1	76	2.2	g′ br B|r	13500	
		11.1	f′		23.1	—	2.2	Do.	14500	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture s.	Corona Colors.	Number n.	Remarks.
1903	July 18	12.4	c		23.1	76	2.3	w br B|r	15500	
		4.3	c R′		23.1	70	1.8	cor	8000	
		5.5	R		23.1	67	2.2	cor	14500	
	July 19	10.4	R′	N.	22.1	66	1.5	cor	4000	Rain all night.
		1.4	c		23.1	66	1.4	cor	3500	
		5.2	c		23.1	68	1.1	cor	1800	
		5.9	c			68	1.5	cor	4000	
	July 20	11.2	f	N.W.	21.1	74	2.6	w r|g	24000	
		11.5	f		22.1	—	2.5	w br B|r	20000	
		12.9	f		22.1	74	2.8	w o|g′	30000	
		1.0	f		22.1	—	2.8	g′ br B|r	28000	
		4.1	f		23.1	72	2.6	w r br B g r	22000	
		5.5	f		23.1	70	2.5	w br B|r	20000	
	July 21	9.7	f	N. E.	22.1	72	1.4	cor small	3500	After cloud-burst
		10.3	c		22.1	—	1.5	cor	4500	and thunder-
		11.9	c		23.1	76	1.6	cor	5000	storm.
		1.0	c		23.1	73	1.7	cor	6000	
		3.7	c R		23.1	70	1.4	cor	3500	
		5.0	c		24.1	70	1.5	cor	4000	
	July 22	9.9	c	N.	22.1	71	1.5	cor	4500	
		11.8	f	S.	—	76	2.0	cor	11000	
		3.0	f		24.1	76	2.4	w br b|p	17500	
		3.4	f		24.1	76	2.4		17500	
		5.5	c		24.1	74	1.8	cor	8000	Storm coming—
	July 23	10.4	f	S. E.	23.1	77	2.3	w br B|r	16500	violent rain
		11.2	f		22.1	—	2.4	w br b g r	17500	storm.
		12.6	c′		23.1	74	2.4	Do. B	17500	
		3.8	c		24.1	77	2.1	w r|g	11500	Storm clouds.
		5.8	f′ (S)		24.1	77	2.2	w br b′ g|p	13500	
		9.0	f′		24.1	72	{ 2.7 2.8	w r|g w r g }	26000	
	July 24	10.3	f	N.W.	22.1	79	2.3	cor	15500	
		11.0	f		22.1	—	2.2	w br B g′ r	14500	
		1.0	f		24.1	82	1.7	cor small	13500	
		3.1	f′		24.1	83	2.2	cor	13500	
		5.9	f		25.1	80	2.0	cor	10000	
	July 25	12.0	f	S. W.	22.1	83	2.3	w br B|r	16500	
		12.7	f		23.1	84	2.1	cor	11500	
		2.8	f		24.1	86	2.5	w r B g	20000	
		4.2	f		24.1	86	2.5	w br p B|r	20000	
		5.5	f		25.1	84	2.2	w r br B g r	13500	
	July 26	9.7	c	W.	23.1	80	2.2	w rp B g|r	13500	
		10.8	c		24.1	84	2.0	w rp B g	10000	
		1.0	c		24.1	86	1.8	cor	7000	
		4.4	f		25.1	86	1.4	cor	3000	
		5.3	f		25.1	—	1.4	cor	3000	
		5.7	f		25.1	84	1.7	cor	6000	
		8.5	f		25.1	77	{ 1.5 1.5	cor cor	4000 4500	
	July 27	10.4	f	N.W.	21.1	68	2.4	w br B|r	17500	
		12.3	f		22.1	72	2.4	w br B|r	17500	
		3.5	f		23.1	73	2.4	Do.	17500	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1903	July 27	5.9	f		23.1	70	2.3	w br|g|r	14500	
	July 28	9.8	f	N.W.	21.1	70	2.9	g′ br B g r	31000	
		11.0	f		21.1	72	2.6	w r|g	22000	
		12.5	f		22.1	74	2.3	w br B g|r	15500	
		3.0	f′ (S)		23.1	76	2.3	Do.	16500	
		5.3	f		23.1	74	2.6	w r|g	22000	
		6.0	f		23.1	—	2.6	Do.	22000	
	July 29	9.5	c	S. W.	22.1	75	2.5	w br B	21000	
		12.3	c		24.1	77	2.2	w r̊|g	13500	
		3.1	c		24.1	78	2.3	w br B|p	16500	
		5.3	c		25.1	75	2.3	w br B g	16500	Storm coming.
	July 30	9.7	f	S. W.	23.1	84	2.8	w r|g	28000	After night's rain.
		10.3	f		24.1	—	2.8	w br B p	30000	
		12.9	f		25.1	89	2.4	w br B	17500	
		3.0	f		26.1	87	2.3	w br B g	15500	
		4.9	f		26.1	85	2.2	w br B g|r	13500	
		5.5	f		27.1	—	2.1	w r|g	11500	
	July 31	9.5	f	W.	24.1	75	2.1	w br b	14500	
		11.9	f		24.1	78	2.3	w br B g|r	15500	
		3.0	c′		25.1	76	2.3	Do.	15500	
		4.4	c		25.1	72	2.2	cor	14500	
		5.6	c		25.1	71	2.1	w r b g r	11500	
	Aug. 1	9.4	f	N.	22.1	70	1.7	cor	6000	
		9.7	f			—	2.3	cor	15500	
		12.4	f		23.1	74	2.3	w br B|r	15500	
		3.1	f		24.1	76	2.1	w br B g r	11500	
		5.5	f		25.1	75	2.1	Do.	11500	
		9.3	f		24.1	66	2.4	w br B|p	17500	
	Aug. 2	9.7	f	N.	23.1	73	1.7	cor small	6500	
		11.4	f		23.1	76	1.9	cor	8500	
		1.4	f		24.1	78	1.7	cor	6000	
		4.8	f		23.1	78	1.5	cor	4500	
		6.0	f		23.1	75	1.3	cor	2500	
		9.5	f		23.1	70	1.8	cor	7000	
		9.8	f		23.1	—	1.9	cor	8500	
	Aug. 3	10.8	c′	N.	22.1	73	3.2	w r B	44000	
		12.4	c′		23.1	76	2.3	w br|g r	15500	
		2.7	c′		24.1	76	2.2	cor	13500	
		4.8	c′		24.1	72	2.0	w br B|r	10000	
		5.8	c′		24.1	70	1.6	cor	5000	
	Aug. 4	9.6	c	N. E.	22.1	66	2.2	w br b g|r	13500	
		12.3	c		22.1	68	2.2	w br b g y r	13500	
		3.6	c R′		23.1	65	2.1	Do.	12500	
		5.8	R		23.1	62	2.0	Do.	10000	
	Aug. 5	12.3	R	E.	21.1	60	1.2	cor small	2000	
		1.0	R		21.1	60	1.5	cor	4000	
		4.7	c R′		21.1	—	2.0	cor	11000	
		6.0	c		21.1	60	1.5	cor	4000	
	Aug. 6	12.3	c	N. E.	20.1	69	1.4	cor	3000	
		1.2	c		20.1	68	1.1	cor small	1800	
		4.4	c		21.1	67	2.1	cor	11500	Thunder.
		5.1	c		21.1	65	2.0	cor	10000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1903	Aug. 6	6.0	c R		22.1	65	2.3	cor	15500	
	Aug. 7	10.7	c	S. W.	20.1	72	2.0	cor	11000	
		12.5	f′ (S)		21.1	77	1.8	cor	8000	
		3.3	f (S)		21.1	77	2.2	w r|g	11500	
		4.9	f		21.1	74	2.0	cor	10000	
		6.0	f		21.1	71	2.1	cor	11500	Clear, windy.
	Aug. 8	9.5	f	N.W.	19.1	65	2.8	w r|g	28000	
		9.9	f		19.1	67	2.8	Do.	28000	
		11.0	f		19.1	70	2.9	w br B	31000	
		12.5	f		19.1	70	2.6	w r|g	24000	
		3.3	c′		21.1	68	2.3	w br B|r	15500	
		5.3	f		—	66	2.4	w r|g	19000	
	Aug. 9	9.0	c R′		20.1	62	2.0	cor w br b g r	10000	
		11.5	c		20.1	64	1.7	cor	6500	
		1.2	c		21.1	65	1.5	cor	4500	
		4.4	c		20.1	66	1.7		6500	
		6.0	c		21.1	65	1.6	cor	5500	
		9.7	c fog		21.1	63	1.9	cor	8500	
	Aug. 10	10.5	f	W.	20.1	75	2.8	w r|g	28000	
		12.7	f′		20.1	80	2.1	cor	11500	
		2.7	f		22.1	77	2.2	cor	13500	
		5.6	f		22.1	77	2.0	w r B g r	10000	
	Aug. 11	9.7	c′	S.	20.1	73	2.8	w r|g	28000	
		10.1	c		20.1	—	2.3	w br b g r	15500	
		11.8	c		21.1	74	2.4	w br b g r	17500	
		12.1	c		21.1	—	2.4	Do.	17500	Fresh water, etc.
		3.7	c R′		22.1	70	2.8	w r|g	28000	
		6.1	c		23.1	69	2.2	cor	13500	
	Aug. 12	9.4	f	W.	20.1	74	2.4	w br B g r	17500	
		9.9	f		—	—	2.4	Do.	17500	
		12.3	f		21.1	76	2.5	w br B|r	21000	New inlet pipe.
		12.5	f		22.1	—	2.3	cor	16500	
		3.1	f		23.1	78	2.1	cor	12500	
		5.6	f		23.1		2.3	w br B|r	16500	
	Aug. 13	10.4	f	W.	20.1	69	2.2	w br b g r	13500	
		10.8	f		20.1	—	2.3	w|B|p	15500	
		4.5	f		20.1	72	2.7	w r|g	26000	
		5.0	f		20.1	—	2.6	w br	22000	
	Aug. 14	9.6	f	W.	20.1	71	1.8	cor	7000	
		10.9	f		20.1	—	2.2	w r|g	13500	
		11.7	f		20.1		2.4	w br B|r	17500	
	Aug. 17	4.0	f	N.W.	21.1	75	2.4	w br B|r	17500	
		5.8	f		22.1	74	2.2	w r b g r	14500	
	Aug. 18	10.5	f	N.W.	—	75	2.9	g′ br B	31000	
		12.0	f		21.1	78	2.8	w r|g	28000	
		3.2	f	S.	22.1	76	2.5	w br b g r	20000	
		4.8	f		23.1	73	1.9	cor	8500	
	Aug. 19	10.5	f		22.1	77	3.1	w b|b|p	38000	New apparatus.
		10.8	f	S.	22.1	—	3.2	Do. br w B p	42000	
		12.5	f		24.1	79	{ 3.0 3.0	w r|g } w r g }	35000	
		3.2	f		25.1	80	2.5	w br b|r	20000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1903	Aug. 19	3.8	f		25.1	—	2.1	cor	11500	
		4.3	f		25.1	—	2.4	w br b|p	17500	
		5.8	f		—	74	2.8	w r|g	28000	
	Aug. 20	9.1	c	S.	23.1	76	3.0	w r|g	36000	
		10.2	c		24.1	76	3.0	w r|g	35000	
		12.3	c R′		24.1	78	2.6	cor	22000	
		12.7	c		24.1	—	2.9	w r|g	31000	
		3.2	R		25.1	73	2.2	w br b|r	14500	
		4.0	R′		25.1	—	2.4	cor	19000	
		5.7	R′		26.1	72	1.7	cor	6000	
	Aug. 21	9.2	f	N.W.	23.1	71	—	—	—	Open trench at Wilson Hall.
		11.3	f		23.1	77	2.4	cor	17500	
		12.2	f		23.1	77	2.4	cor	17500	
		4.7	f		25.1	77	2.5	cor	21000	
		6.0	f		25.1	73	2.5	w br b|r	21000	
	Aug. 22	9.2	f	W.	—	—	2.9	g br B r	31000	
		10.1	f		23.1	78	3.0	g b|p	35000	
		12.0	f		24.1	83	3.1	w br B|r	38000	
		12.7	f		24.1	83	3.0	Do. { above / w r|g }	35000	
		4.1	f		26.1	83	2.4	cor	17500	
		5.5	f		26.1	81	2.6	cor	22000	
		6.0	f		26.1	—	2.4	w br b|r	17500	
	Aug. 23	10.1	f	W.	24.1	81	2.1	cor	11500	
		10.5	f		24.1	—	2.1	cor	11500	
		12.7	f		—	83	1.8	cor	8000	
		4.7	f		25.1	84	1.6	cor	5500	
		5.9	f		25.1	82	1.9	cor	9500	
	Aug. 24	9.6	c′ R′	N.W.	23.1	73	3.5	w r|g	53000	
		9.8	f′ S		23.1	—	3.3	w p b g′ r	47000	
		12.2	f′ S		23.1	77	3.5	w r|g	55000	
		12.4	f′	N.W.	24.1	—	3.5	w r|g	53000	
		3.1	f		25.1	78	2.2	cor	13500	
		5.2	f		25.1	76	2.1	cor	11500	
	Aug. 25	10.3	c R	N.W.	22.1	63	2.8	g′ b p	28000	
		12.5	c′		—	71	2.0	cor	10000	Window open.
		3.0	c′		24.1	74	2.2	cor	13500	" "
		5.3	c R		25.1	74	2.9	w r g	31000	
	Aug. 26	9.8	c	N.	22.1	66	1.5	cor	4000	Violent rain.
		10.2	c		22.1	—	1.5	cor	4000	
		12.2	c		22.1	67	1.7	cor	6000	New pipe.
		12.8	c		—	—	1.6	cor	5500	New adjustment.
		3.3	c		23.1	70	1.4	cor	3500	
		3.7	c		—	—	1.4	cor	3000	
		4.1	c		23.1	—	1.5	cor	4500	
		5.5	c′ to c		23.1	66	1.7	cor	6500	
		5.7	c		—	—	1.8	cor	8000	
	Aug. 27	9.8	f	N.	21.1	70	2.9	g′ br b	31000	
		10.5	f		21.1	—	2.8	g′ br b	28000	
		11.1	f		—	—	2.6	w r|g	23000	Glass clean, new water.
		11.6	c′		22.1	74	2.4	w br b|r	17500	
		12.9	c		22.1	74	2.4	cor	17500	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1903	Aug. 27	3.4	c		23.1	74	2.2	cor	13500	
		3.8	c		23.1	—	2.2	cor	13500	
		5.8	c		23.1	69	2.0	cor	10000	
		6.0	c		—	—	2.0	cor	10000	
	Aug. 28	9.6	c	N. E.	21.1	69	2.2	cor	14500	
		12.3	c		22.1	71	3.3	cor above g′	45000	
		12.4	c		—	—	3.0	g′ br b p	35000	
		3.3	c R′		22.1	66	2.7	w r|g	25000	
		3.8	c		22.1	—	2.6	cor	22000	
		5.7	c R		—	63	1.9	cor	8500	
		5.8	c		22.1		1.9	cor	8500	
	Aug. 29	9.9	R	E.	20.1	63	2.7	w r|g	25000	New pipe.
		10.1	R		20.1	—	2.2	cor	13500	
		12.8	R′		21.1	62	1.5	cor	4000	
		3.3	R′		22.1	63	1.5	cor	4000	
		5.7	R′		22.1	61	2.1	cor	11500	
	Aug. 30	10.8	R	E.	20.1	64	1.7	cor	6000	
		12.5	R		21.1	63	1.6	cor	5000	
		5.1	R		20.1	61	1.3	cor	2500	
	Aug. 31	9.7	R′	N.	19.1	61	1.8	cor	8000	Stagnant air
		9.9	—		19.1	—	1.9	cor	8500	
		12.1	c		20.1	62	1.9	cor	8500	
		4.0	c		21.1	63	1.9	cor	8500	
		5.5	c		21.1	62	1.9	cor	8500	
	Sept. 1	9.6	f	W.	19.1	70	2.9	w br b|p	31000	
		10.3	f′		19.1	—	2.9	cor	31000	
		12.5	f′ (S)		21.1	75	2.4	w r b	49000	
		12.7	f′		21.1	—	3.3	{ w p b g / w br b p }	45000	
		3.3	f′	S.	—	74	2.6	cor	22000	
		5.8	f		22.1	70	2.6	w r|g	23000	
	Sept. 2	9.9	c′	W.	20.1	70	2.3	cor	15500	
		10.9	c′		20.1	—	2.3	cor	15500	
		12.9	c′		21.1	—	2.8	w r|g	28000	
		4.4	c		22.1	70	2.7	w r|g	26000	
		5.8	c		22.1	68	1.9	cor	8500	
	Sept. 3	10.0	f		20.1	67	1.5	cor	5500	
		11.4	f		20.1	72	2.8	w br B|p	28000	
		12.1	f		21.1	73	3.0	Do.	36000	
		2.8	f	S.	—	75	2.8	w r g	28000	
		4.7	f		22.1	73	2.8	Do.	28000	
		8.3	f		22.1	68	2.8	g|b|p	28000	
	Sept. 4	10.3	f	S.	21.1	72	2.5	cor	20000	
		12.4	f		22.1	75	3.0	w|b|p	35000	
		2.4	f		23.1	76	2.5	cor	21000	Fire on campus.
		3.7	f		24.1	74	2.5	cor	21000	
	Sept. 5	9.7	c	S. W.	21.1	72	2.6	cor	23000	
		12.3	c		22.1	77	2.6	cor	22000	
		3.0	c		23.1	71	2.6	cor	22000	
		4.0	R		23.1	75	1.7	cor	6500	Thunder.
		5.6	c′		23.1	67	2.3	cor	15500	Rain over.
	Sept. 6	9.9	f	N.	21.1	65	2.8	cor r|g	28000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1903	Sept. 6	10.8	f		21.1	67	2.8	w r|g	28000	
		12.8	f		22.1	69	2.4	cor	19000	
		5.5	f		21.1	68	2.1	cor	11500	
	Sept. 7	10.7	f	N.W.	20.1	66	2.3	cor	16500	
		1.0	c′		21.1	68	3.2 / 2.8	w br / Do.	42000	
		3.1	c	N. E.	22.1	69	2.8	cor	28000	
		4.2	c		21.1	—	2.4	cor	19000	
		5.5	c		22.1	66	2.4	cor	19000	
	Sept. 8	10.4	f	N.	19.1	63	2.9	w br b	31000	
		12.4	f		19.1	65	3.0	w br b|r	35000	Repeated $s=3.0$.
		2.8	f		20.1	66			26000	" $s=2.7$.
		3.0	f		20.1	—	2.7	w r g	26000	
		5.8	f		21.1	61	2.7	cor	25000	
	Sept. 9	10.2	f	S.	18.1	64	3.3	w p	47000	
		10.4	f		18.1	—	3.4	w p	49000	
		11.9	f		19.1	67	3.1	w br b|r	38000	
		1.0	f		19.1	—	3.1	g′ br b|p	38000	
		2.8	f		20.1	67	2.9	w r|g	33000	Repeated $s=2.7$.
		5.4	f		21.1	64	2.8	w r|g	28000	
		9.6	c		20.1	61	3.0	w r|g	35000	Night.
	Sept. 10	9.9	c		19.1	72				Glass broke.
		10.7	c		19.1	73	3.0	w br b|p	35000	Old apparatus.
		11.2	c		21.1	74	2.9	Do.	31000	
		12.4	c		21.1	74	2.6	cor	22000	
		7.5	f′		21.1	70	2.6	cor	22000	Repeated $s=2.3$.
	Sept. 11	9.5	f	W.	21.1	78	2.9	w r|g	31000	
		11.7	f		22.1	82	2.7	cor	25000	
		12.4	f		23.1	82	2.9	cor	31000	
		2.9	f		24.1	83	3.0	w(br) b|r	35000	
		5.6	f		24.1	77	2.8	w r|g	28000	
	Sept. 12	10.5	f	W.	21.1	73	4.0	g′ o b	75000	
		11.3	f		21.1	75	4.0	Do.	75000	
		12.5	f		22.1	76	3.3	w br	45000	
		3.2	f	S.	23.1	77	2.8	w r|g	28000	
		5.0	f		24.1	72	2.8	w r|g	28000	
	Sept. 13	11.0	f	S. W.	21.1	79	2.8	w br b|r	30000	
		1.7	f		23.1	83	2.0	cor	10000	
		6.8	f		23.1	76	1.6	cor	5000	
		7.0	f		23.1	74	2.0	cor	10000	
	Sept. 14	9.7	f	W.	22.1	83	3.3	w br . . .	45000	
		12.4	f		25.1	88	3.0	w br b g r	35000	
		2.5	f		25.1	88	2.7	cor	25000	
		5.7	f		27.1	84	2.8	w r|g	30000	
	Sept. 15	9.7	f	W.	24.1	81	3.0	w r b g	35000	Repeated $s=3.0$.
		12.5	f		26.1	86	3.6	w r|g	57000	" $s=3.2$.
		2.5	f		26.1	86	3.0	g′|b|r	35000	
		5.7	f		26.1	77	2.8	w r|g	28000	
	Sept. 16	2.3	c	S.	24.1	78	2.0	cor	10000	
		3.7	c		25.1	—	2.0	cor	10000	
		6.1	c		26.1	76	2.0	cor	10000	
	Sept. 17	9.5	c	S. W.	24.1	76	2.2	cor	13500	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture s.	Corona Colors.	Number n.	Remarks.
1903	Sept. 17	12.3	c		26.1	80	2.5	cor	20000	Wind storm.
		3.5	c		26.1	78	2.8	w r|g	28000	Gale.
		6.3	c R		26.1	74	2.2	cor	14500	
	Sept. 18	9.4	c′	N.W.	21.1	65	2.6	cor	24000	
		12.4	c′		22.1	70	2.7	w r|g	25000	
		6.0	c′		22.1	64	2.7	w r|g	25000	
	Sept. 19	9.7	f	N.W.	20.1	62	4.1	g b p	80000	Repeated same.
		12.8	f		21.1	67	3.0	g|b|r	35000	
		3.3	c′		22.1	68	2.6	w r|g	24000	
		5.5	c′		22.1	63	2.8	w r|g	28000	
	Sept. 20	10.4	c′	N. E.	20.1	63	1.5	cor	4000	
		11.9	c′		20.1	63	1.8	cor	7000	
		1.5	c			65	1.8	cor	7000	
		5.4	c		21.1	60	1.9	cor	9000	
		6.4	c		21.1	58	2.1	cor	11500	
	Sept. 21	9.3	c	N.	18.1	59	2.4	cor	17500	
		1.0	f′		20.1	66	3.0	w br B|r	36000	
		2.1	f		20.1	67	3.1	Do.	38000	
		3.0	f		20.1	—	3.0	g′ br b|r	35000	
		5.9	f		21.1	63	3.0	g′|b|p	35000	
		9.0	f		20.1	56	3.3	cor	47000	Night.
	Sept. 22	9.5	f		19.1	—	2.6	cor	22000	
		3.4	f	W.	23.1	78	2.8	w r|g	28000	
		5.2	f		23.1	75	2.9	cor	31000	
		6.0	f		23.1	—	3.1	w|b|p	38000	
	Sept. 23	9.4	f	S. E.	19.1	67	2.8	w r|g	30000	
		12.4	f		21.1	74	3.0	w o|g	35000	
		6.0	f		23.1	68	3.3	cor	45000	
		6.2	f		23.1	—	2.9	w b p	33000	Repeated.
	Sept. 24	9.2	c R′	W.	20.1	65	2.8	w r|g	28000	
		12.2	c		21.1	69	2.8	Do.	28000	
		2.9	c		20.1	67	2.8	g′|b|p	30000	
		6.0	f′		21.1	61	2.7	w r|g	25000	
	Sept. 25	9.2	f	N.W.	17.1	56	3.7 3.8	w r|g w r g	34000	
		9.5	f		17.1	—	3.8	Do.	66000	
		11.7	f			63	3.4	w br b|g	49000	
		3.2	f		20.1	65	3.2	w|b|p	42000	
		6.0	f		20.1	60	3.4	w r|g	49000	
		9.4	f		20.1	55	3.0	w|b|p	36000	
	Sept. 26	9.6	f	S.	18.1	63	3.3	w r|g	47000	
		9.8	f		18.1	—	3.4	wr|g	51000	
		12.9	f		22.1	69	2.7	w r|g	26000	
		4.0	f		21.1	70	2.9	w|b|p	31000	
		6.0	f		21.1	64	2.9	Do.	31000	g′/b/p
	Sept. 27	9.8	f to c	S. W.	19.1	70	2.1	cor	11500	
		12.0	R′		21.1	69	2.0	cor	11000	
		4.7	c		20.1	71	2.7	w r|g	25000	
		6.5	c		21.1		2.3	cor	15500	
	Sept. 28	9.5	f		18.1	61	2.8	cor	28000	Rain and storm
		12.0	f		18.1	62	2.9	cor	31000	at night.
		5.8	f		20.1	57	2.9	w o bg	31000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1903	Sept. 29	9.5	f		17.1	54	3.0	w br B|r	35000	
		12.5			18.1	57	3.3	Do.	45000	
		3.8	f		18.1	55	3.0	w o g	35000	
		6.3	f		—	50	3.2	w br	42000	
		9.0	f		19.1	46	3.1	w|b	38000	Night cold.
	Sept. 30	9.3	f	W.	17.1	57	3.8	w r|g	68000	
		9.8	f		17.1	—	4.0	g′|b|p	75000	Cold.
		12.4	f		18.1	64	3.6	w r|g	58000	
		3.5	f		19.1	66	3.1	w br b|r	38000	
		6.2	f		20.1	60	2.8	g b|p	28000	
	Oct. 1	9.7	f′	S. W.	17.1	65	3.1	w br b|r	38000	
		1.0	f		19.1	74	3.1	Do.	38000	
		3.7	f		21.1	73	2.6	w o g	22000	
		5.9	f		21.1	68	3.1	w br b|r	38000	
	Oct. 2	9.4	c	W.	19.1	67	2.3	cor	15500	
		1.0	c		21.1	73	2.2	cor	14500	
		4.0	c	N. E.	21.1	68	1.8	cor	7000	
		5.8	c		22.1	65	1.8	cor	8000	
	Oct. 3	9.3	f	N. E.	18.1	59	1.8	cor	8000	
		10.0	f		18.1	—	2.5	cor	20000	
		12.0	f		19.1	66	2.8	g′ b B|r	28000	
		3.0	f		21.1	68	2.7	cor	25000	
		5.8	f		21.1	59	2.3	cor	16500	
	Oct. 4	10.4	f	S.	19.1	62	2.9	cor	31000	
		10.7	f		19.1	—	2.8	g′|B|p	28000	
		12.4	f		20.1	64	2.9	g′|b|p	33000	
		6.2	f		19.1	62	2.9	w r g	31000	
	Oct. 5	9.3	f′	W.	19.1	69	3.2	w r . . .	42000	
		9.9	f		19.1	—	3.6	w r|g	58000	
		12.4	c′	.	21.1	76	3.0	w|B|p	35000	
		5.1	c R		23.1	67	2.8	g′ b|p	28000	
		6.0	R		22.1	67	3.2	w r g	42000	
	Oct. 6	9.4	f′	N.W.	19.1	65	2.2	w|B|p	13500	
		10.0	f′		20.1	—	2.2	Do.	13500	
		12.1	f		20.1	70	2.2	cor	14500	
		3.5	f	S. E.	22.1	69	2.7	cor	25000	
		6.6	f		22.1	61	2.5	cor	20000	
		10.9	f		21.1	58	2.0	cor	11000	Night.
	Oct. 7	9.2	c	E.	20.1	63	2.1	cor	11500	
		12.6	c		21.1	64	1.8	cor	7000	
		2.9	c R′		21.1	64	1.8	cor	7000	
		6.0	c R′		22.1	60	2.1	cor	11500	
	Oct. 8	9.7	c	S. E.	20.1	66	3.0	w r|g	35000	Repeated $s=2.5$.
		12.2	c		—	68	2.9	w r|g	31000	
		2.8	c′		21.1	68	3.0	w|B|p	35000	
		6.2	c′		22.1	62	2.2	cor	13500	
	Oct. 9	9.1	f	E.	20.1	65	1.6	cor	5000	Rained at night.
		1.0	c		22.1	66	1.6	cor	5000	
		3.0	c		22.1	66	1.5	cor	4000	
		6.0	c		22.1	61	1.7	cor	6500	
	Oct. 10	9.1	R′	N. E.	20.1	55	1.8	cor	7000	Floods in New York.
		12.8	R′		21.1	57	1.7	cor	6000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture s.	Corona Colors.	Number n.	Remarks.
1903	Oct. 10	6.0	R′		22.1	55	1.8	cor	7000	
	Oct. 11	9.9	R′	N. E.	20.1	55	2.1	cor	11500	
		12.4	R′		21.1	55	1.8	cor	8000	
		5.0	R′		20.1	54	1.7	cor	6000	
		6.2	R′		21.1	54	1.9	cor	8500	
	Oct. 12	9.4	R	N.	19.1	52	2.3	cor	15500	
		12.8	R		19.1	55	2.9	y o|g	31000	Repeated $s=3.0$.
		4.3	c		21.1	55	2.7	w r|g	25000	
		6.3	c		21.1	55	2.5	cor	20000	
	Oct. 13	9.5	c	N.	19.1	57	2.5	w|B|r	20000	
		12.0	c		20.1	59	2.3	Do.	15500	
		3.6	c		21.1	60	--	—	—	
		6.4	c		20.1	56	2.8	w r|g	28000	
	Oct. 14	9.4	f	N.	17.1	59	3.7	w r|g	64000	Fine weather.
		9.8	f		17.1	—	4.1	g′ c b′	30000	
		11.7	f		19.1	68	3.6	w br	57000	Sun spots.
		12.9	f		20.1	68	3.1	w|B|p	38000	
		1.3	f		20.1	—	3.3	wbr	47000	
		3.2	f		20.1	68	3.1	—	38000	
		4.8	f		20.1	64	2.6	cor	22000	
		5.5	f		20.1	63	2.4	cor	17500	
	Oct. 15	9.4	f		18.1	55	2.9	w|b|r	31000	
		12.5	f		19.1	61	3.8	w r|g	66000	
		2.8	f		19.1	61	2.8	w r|g	28000	
		6.0	f		20.1	55	3.0	g′ B p	35000	
	Oct. 16	9.7	f′	S.	18.1	58	3.3	w p . . .	45000	
		10.0	f		18.1	--	3.0	w|B|r	35000	
		12.0	f		19.1	65	3.0	g|B|p	35000	
		4.4	c		21.1	64	2.7	w r|g	25000	
		6.3	c		21.1	63	2.7	w r|g	25000	
	Oct. 17	9.8	c	S.	—	65	2.7	w r g	25000	
		1.3	R		21.1	66	2.9	g B p	31000	
		3.7	R		22.1	66	2.9	w|b g r	31000	
		6.0	R		22.1	61	2.5	w br	20000	
	Oct. 18	10.0	c′	W.	19.1	59	2.3	cor	15500	
		12.3	c R		20.1	60	2.5	cor	20000	
		4.4	f		20.1	54	2.5	w r|g	21000	
		6.2	f		20.1	49	2.6	cor	22000	
	Oct. 19	9.3	f	W.	18.1	48	3.9	y o bg	70000	
		9.8	f		18.1	—	3.5	w r g	55000	
		11.7	c		19.1	53	3.1	w|b|p	38000	
		3.7	f		20.1	55	3.0	Do.	35000	
		6.0	f		21.1	52	3.1	w br	40000	
	Oct. 20	9.4	f	S. W.	19.1	62	2.8	g′|B|p	30000	
		1.0	f		20.1	67	2.9	Do.	31000	
		2.0	f		20.1	68	2.9	cor	36000	
		6.5	f		22.1	60	2.9	g|B|p	31000	
	Oct. 21	9.4	f	N.W.	18.1	57	3.2	w|b p	42000	
		9.8	f		18.1	—	3.6	w r g	57000	
		1.2	f		20.1	58	3.6	Do.	59000	
		2.7	f		20.1	59	3.1	w|b|p	38000	
		6.0	f		20.1	54	3.1	Do.	38000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s.*	Corona Colors.	Number *n.*	Remarks
1903	Oct. 22	9.3	f	N.W.	18.1	50	2.8	w r|g	30000	
		1.4	f	S.	20.1	57	2.7	cor	27000	
		4.0	f		20.1	56	2.8	w r g	28000	
		5.7	f		21.1	55	3.2	w r g	44000	
	Oct. 23	9.3	c′	S. W.	19.1	65	3.0	cor	36000	
		12.0	c		20.1	69	3.0	w r|g	35000	
		4.2	c R′		21.1	57	2.4	cor	17500	
		5.8	c		21.1	56	2.4	cor	17500	
	Oct. 24	9.4	c	N.W.	19.1	48	3.0	g|b|p	35000	
		12.0	c′		20.1	51	3.4	w p cor	49000	
		3.5	c′		20.1	51	2.9	g|b|p	31000	
		6.0	c′		20.1	48	2.9	g B p	31000	
	Oct. 25	10.4	f	N.	18.1	45	4.3	gy o bg	90000	
		10.8	f		18.1	45	4.0	w o g	75000	
		12.3	c		18.1	48	3.0	g|b|p	35000	
		5.0	c		17.1	45	2.8	w r|g	30000	
		6.5	c		17.1	45	2.8	Do.	30000	
	Oct. 26	9.4	f	W.	16.1	46	3.1	w B g	38000	
		10.0	c (S)		16.1	—	2.7	cor	25000	Clouds.
		11.7	f		16.1	44	2.4	rop cor	70000	
		3.4	f′		19.1	43	2.9	w|b|p	31000	
		6.0	f		20.1	38	2.8	w|b|p	28000	
	Oct. 27	9.6	f	W.	19.1	39	3.3	rop . . .	47000	
		12.8	f		21.1	42	3.4	w r|g	49000	
		5.8	f		22.1	38	3.2	w|b|g	42000	
	Oct. 28	9.4	f		—	39	4.0	y o bg	75000	Snow.
		9.9	f	N.W.	19.1	—	4.1	Do.	80000	
		1.4	f		20.1	46	3.7	w rg	62000	
		3.2	f		21.1	46	3.1	w B|p	40000	
		6.0	f		22.1	41	3.1	Do.	38000	
	Oct. 29	9.3	f		19.1	45	3.4	w p b|r	49000	
		2.8	f		23.1	62	3.5	Do.	53000	
		6.0	f		23.1	56	3.5	w r|g	53000	
	Oct. 30	9.5	f	W.	21.1	59	3.1	w|b|p	38000	
		12.7	f		22.1	68	2.5	cor	20000	
		3.1	f		23.1	68	2.7	w|b|p	25000	
		5.8	f		23.1	62	3.6	w r g	57000	
	Oct. 31	9.2	f	W.	21.1	63	2.6	cor		
		9.9	f		20.1	—	3.2	w r	42000	
		12.2	f		21.1	69	2.9	g′|b′|p	33000	
		4.2	f		22.1	68	3.0	w|b|p	35000	
		5.8	f		—	64	3.0	Do.	35000	
	Nov. 1	10.8	f	N.W.	19.1	62	3.0	w|b|r	37000	
		12.0	f		19.1	63	3.0	cor	35000	Apparatus cleaned.
		12.4	f		20.1	—	2.9	w r|g	33000	
		4.5	f		20.1	61	2.5	cor	20000	
		6.3	f		—	57	3.0	g′ b|p	37000	
	Nov. 2	9.4	f	W.	—	58	3.7	w r g	61000	
		1.0	f		20.1	65	3.2	w b|p	42000	
		4.1	f		21.1	64	3.0	w o|g	35000	
		5.8	f		21.1	60	3.5	w r|g	53000	
	Nov. 3	9.2	f	W.	17.1	58	3.4	w r|g	49000	

TABLE 1.—*Continued.*

Year	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture s.	Corona Colors.	Number n	Remarks
1903	Nov. 3	12.5	f		19.1	65	3.2	w|b|p	42000	
		3.5	f		20.1	66	2.7	w r|g	25000	
		5.2	f		21.1	61	3.6	w rg	57000	
	Nov. 4	9.3	f	W.	19.1	61	2.9	w o|g	31000	
		12.3	f		20.1	70	3.1	cor	38000	
		2.6	f		21.1	71	2.9	w r|g	31000	
		5.5	f		21.1	66	3.5	w c|g	53000	
	Nov. 5	9.3	c R′	S. W.	19.1	60	2.9	cor	33000	
		11.6	c R		21.1	62	2.8	w r|g	28000	
		4.5	c′		22.1	64	3.2	wp cor	42000	
		5.9	c		23.1	62	2.5	cor	20000	
	Nov. 6	9.1	c		19.1	40	3.0	w o|g	35000	
		10.1	c		20.1	40	3.0	Do.	35000	
		12.4	c		20.1	38	3.0	g B|p	35000	Snow.
		3.2	Snow		20.1	37	3.0	cor	35000	
		5.7	c		22.1	37	3.0	w|b|p	35000	
	Nov. 7	9.6	f		20.1	36	3.4	w p cor	49000	
		10.0	f	W.	20.1	—	3.1	g′ b|p	40000	
		1.3	f		18.1	40	3.1	Do.	38000	
		3.5	f		22.1	41	2.6	w r|g	24000	
		5.9	f		—	38	3.5	w r|g	53000	
	Nov. 8	9.9	f	N.W.	23.1	44	3.4	w r|g	49000	
		12.2	f		24.1	50	2.9	g′ |b′|p	31000	
		5.1	f		24.1	48	2.9	w|b|p	31000	
	Nov. 9	9.2	f	W.	22.1	48	3.9	yg o bg	70000	
		9.6	f		22.1	—	4.2	g′ o b′	85000	
		12.9	f		22.1	60	3.6	w r|g	57000	
		4.0	f		23.1	58	3.0	w|b|r	35000	Repeated $s=2.8$.
		6.0	f		23.1	52	3.4	w r g	49000	
	Nov. 10	9.6	f	S. W.	20.1	53	3.0	w|b|r	35000	
		12.1	c		21.1	58	3.0	Do.	35000	
		3.8	c		21.1	58	3.9	w r|g	70000	
		5.9	f		—	53	2.8	w|b|p	28000	
	Nov. 11	9.5	f	N.W.	18.1	50	2.8	w|b|p	28000	
		12.7	f		19.1	57	2.2	cor	13500	
		12.9	f	N. E.	19.1	—	2.3	cor	15500	
		2.9	f		19.1	56	2.2	cor	13500	
		5.5	f		20.1	49	2.7	cor	25000	
	Nov. 12	9.5	f′	W.	18.1	52	2.2	cor	14500	
		12.5	f′ (S)		18.1	56	3.4	y′ p|g	49000	
		3.0	f		19.1	57	3.0	w|b|r	35000	
		6.0	f		19.1	50	3.9 3.9	g′ br b w r bg	70000	
	Nov. 13	9.5	f	S. W.	17.1	52	3.7	y′ p|g	61000	
		12.7	f		18.1	59	3.3	w r|g	45000	
		4.8	f		—	56	3.3	w r|g	45000	
		5.7	f		19.1	54	3.3	w c|g	47000	
	Nov. 14	9.5	c	N.W.	18.1	48	2.7	w|b|p	25000	
		11.5	c		18.1	48	3.0	cor	35000	
		4.1	f′	W.	18.1	47	3.2	w p cor	42000	
		5.9	f		18.1	44	3.9	g′ o bg	70000	Repeated same.
	Nov. 15	10.2	f	W.	17.1	42	3.5	w c|g	53000	

TABLE 1—*Continued.*

Year	Date	Time	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture s.	Corona Colors.	Number n	Remarks.
1903	Nov. 15	12.5	f		—	44	2.8	g|b|p	28000	
		7.4	f		16.1	39	3.4	w r|g	49000	
	Nov. 16	9.3	c	N.W.	16.1	40	3.2	w p	42000	
		11.5	R		16.1	42	2.8	w o|g	28000	
		3.4	R		18.1	43	2.7	w br b|r	25000	
		5.7	R	N. E.	18.1	44	2.7	g′ b p	25000	
	Nov. 17	9.5	R	N.W.	17.1	40	2.8	g′|b|p	28000	
		12.2	R		18.1	43	{ 3.5 / 3.5 }	{ wp / w c g }	53000	
		3.5	R		19.1	57	3.4	w c g	49000	
	Nov. 18	9.7	c	N.W.	18.1	43	2.8	w o|g	28000	
		12.7	c		17.1	44	2.8	Do.	28000	
		5.7	f′		20.1	39	2.8	g′|b p	28000	
	Nov. 19	9.4	f	W.	19.1	34	3.3	w p bg′ r	47000	
		12.3	f		19.1	40	3.3	Do.	45000	
		5.3	f		20.1	36	3.3	Do.	45000	
	Nov. 20	9.5	f	N.W.	21.1	32	3.1	w|B|p	40000	
		11.9	f	N.	20.1	36	3.4	w p b g′ r	49000	
		4.3	f		20.1	36	3.3	Do.	45000	
		6.1	f		21.1	33	3.8	w r|g	66000	
	Nov. 21	9.4	f	N.	21.1	29	3.2	w br b|r	42000	
		1.3	f		21.1	38	3.2	Do.	42000	
		4.4	f		21.1	36	3.2	w p b g r	42000	
		6.2	f		21.1	35	2.8	g b p	28000	
	Nov. 22	9.8	c	N.	21.1	36	{ 3.1 / 3.0 }	{ w br b|p / w|b|p }	38000	
		1.0	c		21.1	41	2.7	w r|g	25000	
		5.0	c		22.1	39	3.2	w p b g r	42000	
		6.6	c		19.1	38	3.2	w p b g r	42000	
	Nov. 23	9.3	c′	N.	21.1	37	3.8	y′ r|g	66000	
		10.0	c		22.1	—	4.0	g b p	75000	
		12.8	c		21.1	43	2.7	w r|g	26000	
		3.6	c	S.	22.1	43	2.7	w r|g	25000	
		5.4	c R		22.1	33	3.1	w p b g r	40000	
	Nov. 24	9.3	f	W.	22.1	42	3.3	w p b g′ r	45000	
		12.8	f′		20.1	44	2.8	cor	30000	
		3.7	c		20.1	40	2.7	w r|g	25000	
		6.0	c		21.1	35	2.5	cor	21000	
	Nov. 25	9.3	f	W.	22.1	26	3.0	g′ b|p	35000	
		9.7	f		22.1	—	3.7	w r|g	61000	
		11.4	f		21.1	31	3.9	y′ or|g	70000	Cold wave.
		3.2	f		—	31	2.9	g′|b|p	31000	
		5.3	f		21.1	26	2.9	Do.	31000	
		6.0	f		—	—	2.9	Do.	31000	
	Nov. 26	10.0	f	N.W.	22.1	25	3.6	w r|g	57000	
		1.0	f		22.1	29	{ 4.0 / 4.0 }	{ gy o bg / y o bg }	78000	
		5.3	f		22.1	27	3.5	w r|g	53000	Repeated $s=3.6$.
	Nov. 27	9.4	f	N.	21.1	20	3.8	w o|g	66000	130/10 *
		12.6	c		21.1	27	3.9	g b p	70000	Repeated same.
		3.0	c		21.1	27	3.5	w r|g	55000	59/5

* Subsidence data, meaning that in 130 sec. the fog line has fallen 10 cm.

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1903	Nov. 27	3.7	c		21.1	—	4.2	gy o –	85000	69/5
		5.5	c		21.1	27	4.0	w or|g	75000	Repeated same, 58/5.
	Nov. 28	9.3	f	N.	20.1	26	4.0	w o|g	75000	56/5
		1.2	f		21.1	30	2.9	g′ b p	33000	
		3.4	f		21.1	31	3.2	w br –	42000	
		6.1	f		21.1	28	3.8	w r g	66000	59/5
	Nov. 29	10.6	c	N.W.	21.1	24	2.9	g′|b|r	31000	28/5
		11.7	c′		21.1	27	2.9	Do.	31000	43/5
		1.4	c Sun		21.1	26	2.9	Do.	31000	39/5
		5.2	c Sun		21.1	27	3.4	w r|g	49000	
		5.9	c Sun		21.1	—	3.0	w|b|p	35000	41/5
		6.5	c		21.1	—	3.0	Do.	35000	
	Nov. 30	9.3	f	W.	20.1	25	3.0	w r g	35000	47/5
		12.0	f		19.1	32	3.7	w r g	64000	49/5
		3.2	f		19.1	34	3.0	g|b|p	35000	39/5
		5.7	f		20.1	30	4.0	w y r bg	75000	65/5
	Dec. 1	9.3	f	N.W.	20.1	26	4.0	w r g	75000	63/5
		12.7	f		19.1	33	3.0	g b|p	35000	32/5
		3.4	f		19.1	34	2.9	w r|g	31000	26/5
		6.0	f		19.1	30	2.9	w r g	31000	41/5
	Dec. 2	9.4	c Sun		20.1	30	3.6	w r g	59000	53/5
		12.8	c	N.	20.1	36	3.6	w r g	57000	48/5
		3.5	c R′		—	34	3.8	y′ o g	66000	47/5
		6.0	c		20.1	34	3.7	w r g	61000	40/5
	Dec. 3	9.5	c	N.	21.1	31	3.5	w c g′	53000	58/5
		11.8	c		20.1	33	4.0	y o bg	75000	66/5
		3.0	c R′		—	34	3.1	g|b|p	38000	36/5
		5.6	c		22.1	33	3.9	g b p	70000	70/5. Repeated $s=3.2$
		6.0	c		22.1	—	4.1	g′ o bg	80000	
	Dec. 4	9.5	c	N.	21.1	34	3.6	w r g′	57000	
		12.0	c		22.1	37	3.6	w r|g	57000	
		3.2	f′		22.1	39	3.2	w|b|p	42000	
		6.0	f		21.1	35	3.8	w r|g	66000	
	Dec. 5	9.3	c′	W.	—	39	4.2	g′|B p	85000	
		9.7	c		22.1	—	4.2	Do.	85000	
		12.8	c		—	44	3.5	up	53000	
		4.4	c		22.1	40	3.0	w r|g	53000	
		6.0	f′		23.1	40	3.5	w r|g	53000	
	Dec. 6	10.0	f	N.W.	23.1	33	3.2	g|b|p	42000	
		12.3	f		23.1	38	3.1	g br b|p	40000	
		4.5	f		23.1	35	3.0	Do.	35000	
	Dec. 7	9.3	f	W.	22.1	—	{3.9 {4.0	w o|g } y o bg }	70000	
		12.7	f		22.1	39	3.5	w p|g r	53000	
		4.3	f		22.1	37	4.1	gy′ o bg	80000	
		6.1	f		22.1	35	4.1	y′ r bg	80000	
	Dec. 8	9.6	f	W.	22.1	35	3.5	wp cor	53000	
		12.3	f		22.1	43	2.6	cor	22000	
		12.8	f		22.1	—	2.5	cor	21000	
		4.6	f		21.1	41	3.6	w r g	57000	
		6.0	f		22.1	—	3.6	w r g	59000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Apertures.	Corona Colors.	Number *n*.	Remarks
1903	Dec. 9	9.5	c	N.	20.1	36	3.0	cor	35000	
		12.5	c		21.1	40	2.9	cor	31000	
		4.7	R′	N. E.	22.1	42	2.6	cor	22000	
		6.0	R′		22.1	—	2.1	cor	12500	
	Dec. 10	9.3	f	W.	22.1	39	3.3	wp cor	45000	
		12.8	f		21.1	43	3.5	w r g	53000	
		5.8	f		22.1	37	3.1	cor	38000	
	Dec. 11.	9.4	f	W.	21.1	30	3.2	cor	42000	
		12.4	f		20.1	36	3.5	wrg	53000	
		3.1	f		21.1	37	3.5	w p|g	53000	
		6.0	f		21.1	34	{ 4.1 { 4.1	g′ o bg } g b p }	90000	
	Dec. 12	9.9	f	W.	20.1	30	4.0	y′ o g	78000	
		10.5	f		20.1	—	4.1	y o g	80000	
		1.0	c		20.1	37	3.8	y′ o g	66000	
		4.0	c (S)			37	3.8	w y bg	66000	
		6.1	c		21.1	34	3.5	w r	53000	
	Dec. 13	10.4	R	S. W.	19.1	54	2.3	cor	15500	
		1.5	f′		20.1	41	2.2	cor	13500	
		6.0	f Cold		21.1	32	2.6	cor	22000	
		7.0	f		20.1	30	2.6	cor	22000	
	Dec. 14	9.8	f	W.	16.1	24	4.1	g′ o bg	80000	
		10.1	f		17.1	—	4.2	w r g	85000	
		1.1	f		16.1	27	3.7	w r|g	61000	
		6.0	f		17.1	23	4.1	y o bg	80000	
	Dec. 15	9.0	c	W.	18.1	20	4.0	w o g	75000	
		12.6	c′		18.1	26	4.0	w o g	78000	
		3.5	c		18.1	25	2.9	w|b|p	31000	
		6.4	f		18.1	22	3.4	w p cor	49000	
	Dec. 16	9.8	f	W.	18.1	23	3.6	w c|g	57000	Repeated same
		12.5	f		18.1	27	3.6	w p b g	57000	
		3.9	f		18.1	26	3.7	w o|g	61000	
		6.0	f		18.1	24	{ 4.1 { 4.1	gbp } g b p }	80000	
	Dec. 17	8.7	f	W.	18.1	15	3.8	w r g	66000	
		12.3	f		18.1	25	{ 4.2 { 4.2	w o bg } w o g }	85000	
		4.6	f		19.1	28	4.2	w o bg	85000	
		6.4	f		19.1	27	4.2	Do.	85000	
	Dec. 18	9.5	f	N.W.	19.1	16	4.4	g′ o bg′	95000	
		9.8	f		19.1	—	4.0	w r g	75000	
		1.0	f		19.1	18	4.3	g′ br b	90000	
		6.0	f		20.1	15	4.2	w o g′	85000	
	Dec. 19	9.5	f	W.	18.1	21	4.1	g b p	80000	
		10.5	f		18.1	24	4.0	w o g	75000	
		1.0	f		19.1	30	4.0	w o g	78000	
		6.0	f		20.1	28	4.4	y′ o g′	95000	
	Dec. 20	10.3	R		20.1	45	3.7	w c g	61000	
		12.3	R′		21.1	47	2.8	g′ B p	28000	
		6.0	R		22.1	51	2.3	cor	15500	
	Dec. 21	9.8	f	W.	22.1	40	2.9	g′ B p	31000	
		12.5	f		22.1	40	2.9	g′ B p	31000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Apertures.	Corona Colors.	Number n.	Remarks.
1903	Dec. 21	6.3	f		23.1	37	3.5	w r g	53000	
	Dec. 22	9.5	c R′		20.1	39	3.6	w r g	57000	
		12.8	c	W.	21.1	40	3.1	w|b|r	38000	
		6.0	f		21.1	28	3.1	Do.	38000	
	Dec. 23	10.1	f	S. W.	21.1	28	4.0	w o g	75000	
		10.5	f		21.1	—	4.1	g b p	80000	
		11.5	f		—	31	4.2	g′ o b	85000	
		4.0			21.1	35	4.0	y′ o g	75000	
		6.0	f		22.1	35	4.2	w o g′	88000	
	Dec. 24	10.1	f	S. W.	22.1	38	4.2	g′ o bg	85000	
		10.8	c		22.1	43	4.2	g′ o bg	85000	
		12.7	c		22.1	47	3.4	w p cor	49000	
	Dec. 25	10.9	c	W.	23.1	47	2.9	g′ b p	31000	
		1.3	c		23.1	43	2.8	g′ b p	30000	
	Dec. 26	10.2	c	N.W.	23.1	35	2.4	cor	17500	Repeated same.
		1.3	Snow		22.1	25	3.8	w b p	66000	
		1.6	Snow		22.1	—	3.9	g b p	70000	
		4.0	c		23.1	20	4.0	g b p	75000	
		5.3	c		23.1	18	3.4	w r b g	49000	
		6.0	c		22.1	17	{3.0 2.9}	{g′|B|p cor}	35000	
	Dec. 27	9.4	c	S. W.	21.1	13	4.1	y o bg	80000	
		10.8	c		21.1	15	3.9	y′ o bg	73000	
		12.9	Sun		20.1	17	3.4	up cor	49000	Repeated same.
		5.2	c		21.1	22	3.6	w r g	57000	
		7.0	c		21.1	23	3.6	w r g	57000	
	Dec. 28	9.6	f	N.W.	20.1	17	3.5	up cor	55000	
		1.0	f		20.1	19	{4.2 4.2}	{y o bg g′ o bg}	88000	
		3.4	f		20.1	17	4.1	y r g	80000	
		6.1	f		21.1	14	4.1	y r g	80000	
	Dec. 29	10.9	c	S. E.	19.1	13	4.0	y′ r g	75000	
		12.8	Snow		18.1	16	3.1	g b p	38000	
		3.3	c Sun′		18.1	20	3.4	w r g	49000	
		6.2	Sun		19.1	20	3.5	wrg	53000	
	Dec. 30	9.8	f	N.W.	19.1	19	4.1	g′ o bg	80000	
		10.1	f		19.1	—	4.0	g b p	75000	
		12.8	f	W.	20.1	29	3.7	w r g	62000	
		3.7	f	W.	20.1	28	3.0	g|b|p	35000	
		6.0	f		20.1	25	4.1	g′ o bg	83000	
	Dec. 31	9.9	f	W.	19.1	22	3.8	w r g	66000	
		1.2	f		21.1	24	3.7	w r g	64000	
		6.5	f		20.1	22	4.2	w o bg	85000	Repeated same.
1904	Jan. 1	10.4	f	W.	20.1	29	3.2	w p b g r	42000	
		1.3	f		21.1	33	3.6	w r g	59000	
		5.9	f		21.1	21	3.2	w br b g r	44000	
	Jan. 2	9.8	c	N.	20.1	9	4.1	g′ o bg	80000	
		10.2	c		20.1	8	4.1	Do.	80000	Snow.
		1.5	c		21.1	9	4.1	{g|b|p g b p}	90000	"
		3.6	c Sun		20.1	11	3.9	w r g	70000	Repeated same.
		6.0	c		20.1	12	4.0	w r g	75000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1904	Jan. 3	10.6	f′		18.1	8	4.4	v′|b|p	100000	
		10.8	f′	N.	19.1	—	4.2	g b p	100000	
		12.0	f		19.1	7	4.3	v′ p cor	100000	
		12.7	f		19.1	9	4.0	g b p	100000	
		1.5	f		19.1	10	4.1	g b p g′ g b p	100000	
		5.6	f		19.1	4	4.0	w r g	75000	
		6.5	f		19.1	3	4.3 4.0	w o bg w rg	90000	
	Jan. 4	9.6	f	W.	17.1	−5	4.3	g b p	100000	
		10.0	f		17.1	0	4.3	Do.	100000	
		12.4	f		17.1	1	4.2	g b p	100000	
		12.7	f		17.1	1	4.1	g b p	100000	
		3.3	f		17.1	1	4.0	w o g	75000	
		4.7	f		17.1	$-\frac{1}{2}$	4.0	w o g	78000	
		6.0	f		17.1	−2	4.0	w o g	75000	
	Jan. 5	9.4	f	W.	16.1	0	4.1	g b p	100000	
		9.8	f		16.1	2	4.1 4.1	g b p w|b|p	100000	
		12.6	f		16.1	13	4.1	g b p	100000	
		4.5	f	N.W.	16.1	14	4.1	g b p	100000	
		6.0	f		17.1	13	4.0	g′ b p	90000	
	Jan. 6	9.7	f	S.	16.1	9	4.0	g b p	100000	
		11.0	f		16.1	18	4.0	Do.	100000	At first v b p.
		1.4	f		17.1	25	4.1	w o bg	83000	
		4.0	f	S. W.	18.1	25	4.1	g b p	100000	
		6.4	f		18.1	24	4.3	w o bg	93000	
	Jan. 7	9.7	f	W.	18.1	25	4.3	g b p	100000	
		12.4	f		19.1	29	2.7	g′|b|p	25000	Repeated same.
		3.7	c	S.	19.1	29	3.9	w o g	73000	" "
		6.0	f Fog		20.1	26	3.9	w o bg	73000	
	Jan. 8	9.5	c	N.	20.1	21	4.1	g′ o not reg.	80000	
		10.0	c		19.1	—	3.9	w o g	70000	
		12.3	c		19.1	29	3.2	cor	42000	
		3.3	Snow		20.1	29	3.9	w o g	70000	Repeated $s = 4.0$.
		5.7	c Snow		21.1	30	3.9	w o g	73000	
	Jan. 9	9.7	Snow	N.W.	—	32	3.1	up cor	38000	
		12.1	c′		21.1	36	3.1	g|b|p	38000	
		4.0	Sun′	W.	22.1	36	2.8	w o g′	30000	
		6.1	—		22.1	34	2.6	cor	23000	
	Jan. 10	10.5	f	W.	23.1	33	3.3	up cor	45000	Repeated $s = 3.2$.
		12.8	f		22.1	34	3.0	g|b|p	36000	
		5.4	f		23.1	28	3.3	up cor	45000	
		6.6	f		23.1	27	3.1	w|b|p	38000	
	Jan. 11	9.2	f	N.W.	22.1	21	4.2	w o g	88000	
		10.0	f		22.1	—	3.6	w r g	59000	
		1.0	f		21.1	29	4.4	w o g	95000	
		3.4	f		22.1	30	3.1	w|b|p	40000	
		4.5	f		—	27	3.1	Do.	38000	
		6.3	f		22.1	26	3.6	w r g	57000	
	Jan. 12	9.6	f	N.	19.1	28	4.3	w o bg	90000	
		11.6	c		19.1	34	4.2	g b p	85000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1904	Jan. 12	1.3	f		21.1	33	3.4	w r g	49000	
	Jan. 13	9.4	c	N. E.	22.1	35	2.8	w br|g	29500	
		1.5	c R	E.	22.1	37	2.8	w o cor	28000	
		3.7	c R		23.1	38	2.6	w r g	22000	
		6.4	c R		22.1	40	2.6	w rg	23000	
	Jan. 14	9.5	f′ S′	S. W.	21.1	34	3.4	w c g	49000	
		12.5	f		19.1	37	4.2	w o bg	85000?	
		1.5	f		19.1	37	3.7	w r g	62000	
		3.7	f′ S′		20.1	36	3.9	w o g	73000	
		5.6	f		21.1	35	3.7	w rg	62000	
	Jan. 15	9.4	f	W.	21.1	27	4.1	g′ br bg	80000	
		1.3	f		21.1	30	3.8	w c g	68000	
		3.3	f		21.1	28	3.4	w r g	49000	
		6.1	f		21.1	24	3.0 / 2.9	w|b|r / cor	36000	
	Jan. 16	9.8	f′	S. W.	21.1	23	3.4	up cor	49000	
		11.3	f		21.1	25	3.9	w o g	70000	
		4.4	c Snow	S.	21.1	—	3.1	cor	38000	
		6.2	R		21.1	38	2.8	w|b|p	28000	
	Jan. 17	10.6	f	W.	22.1	28	2.9	g′|b|p	31000	
		1.5	f		22.1	29	3.3	w br cor	47000	
		5.7	f		22.1	22	3.0	w|b|p	35000	
		6.5	f		22.1	20	3.0	w|b|p	35000	
	Jan. 18	9.3	f	N.W.	20.1	10	4.1	g b p	100000	
		9.7	f		20.1	—	4.1	g b p	100000	
		12.5	f		19.1	14	4.1	g b p	100000	
		4.0	f		20.1	14	4.1	g b p	100000	
		5.9	f		20.1	12	4.2	w o bg	85000	
	Jan. 19	9.6	f	N.W.	18.1	0	4.4	g b p	100000	
		10.0	f		18.1	—	4.3	Do. up	100000	
		11.9	f	N.	18.1	8	4.1	g b p	100000	
		3.8	f		18.1	13	4.0	w o g	75000	
		6.0	f		19.1	12	4.1	g b p	100000	
	Jan. 20	9.5	Snow	N.	18.1	16	4.6	wp cor	100000	To wbp
		9.8	Snow		18.1	18	4.2	Do.	100000	
		11.8	Snow	S. W.	17.1	24	4.2	g b p	100000	
		2.0	c		18.1	26	4.1	g b p	100000	
		4.1	c		18.1	29	4.2	y′ o bg	90000	
		6.0	c		19.1	28	4.0	w r g	75000	
	Jan. 21	9.4	c	N. E.	19.1	32	4.0	w r g	75000	
		11.5	Snow		19.1	33	2.2	cor	13000	
		11.9	Snow		19.1	—	2.8	cor	28000	
		3.8	Snow		19.1	32	2.8	g′ b p	29500	
		6.0	Snow		20.1	32	3.6	w c g	57000	Repeated $s=3.7$.
	Jan. 22	9.8	R	N. E.	21.1	38	2.5	cor	20000	
		12.9	R		21.1	36	2.9	w o g	31000	
		3.4	R		22.1	30	2.9	g b p	31000	
		6.0	R′		21.1	30	3.1	w br b|r	38000	
	Jan. 23	9.8	Fog	S.	22.1	44	4.0	w r g	75000	
		10.1	Fog		—	—	3.5	w c g	53000	
		1.1	Fog	S. W.	22.1	50	3.4	w br cor	49000	
		4.8	Fog	W.	23.1	47	3.2	Do.	42000	

TABLE 1 – *Continued.*

Year	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1904	Jan. 23	6.3	Fog		23.1	46	4.0	w o g	75000	Repeated same.
	Jan. 24	10.1	f	N.W.	21.1	41	2.8	w y cor	30000	
		12.4	f′		20.1	42	2.8	g|b p	28000	
		4.7	f	W.	19.1	36	3.3	wp cor	45000	
		6.4	f		19.1	34	3.4	w c	49000	
	Jan. 25	9.6	f	W.	15.1	17	4.1	g b p	100000	
		12.4	f		16.1	21	4.1	g b p	100000	
		3.4	f		16.1	22	4.2	w o g	85000	
		5.8	f		17.1	22	4.1	Do.	80000	
	Jan. 26	9.3	f	N.	18.1	19	2.8	w|b|p	28000	
		11.7	c	E.	18.1	26	3.7	w r g	62000	
		3.4	c Snow		18.1	28	2.7	w r g	26000	
		5.7	c Snow		19.1	28	2.7	cor	25000	
	Jan. 27	9.6	f	W.	20.1	22	3.8	w r g	66000	
		11.2	f		19.1	24	4.2	w o bg	86000	
		1.0	f		20.1	25	4.1	w o g	80000	
		5.9	f		20.1	20	3.4	w c g	51000	
	Jan. 28	9.5	f		19.1	15	4.3	w o g	93000	
		1.0	c		19.1	22	4.1	w o g	83000	
		6.1	c′ Fog		20.1	24	3.8	w rg	68000	
	Jan. 29	9.5	Snow	N.	19.1	22	4.2	gy|b|p	86000	
		11.4	Snow′		19.1	25	4.3	y′ o bg	90000	
		3.2	Snow		20.1	28	4.3	w y g	93000	
		5.8	Snow		—	24	4.4	w o bg	95000	
		10.6	Snow		21.1	22	3.5	wp cor	55000	
	Jan. 30	10.0	f	N.	20.1	22	4.2	w o g′	85000	
		11.9	f		20.1	27	3.7	w r g	62000	
		4.3	f′		20.1	30	2.8	w|b|p	28000	
		6.3	f		21.1	32	{4.1 {4.3	gb p} wo r}	100000	
	Jan. 31	10.7	f	S. W.	21.1	35	3.8	w r g	66000	
		1.0	f		21.1	38	3.5	wp cor	55000	
		4.7	f′		21.1	36	2.9	cor	33000	
		6.3	f		21.1	36	2.9	cor	31000	
	Feb. 1	9.7	c	N.W.	21.1	39	4.3	y o bg	90000	
		12.6	c	W.	20.1	40	3.6	w r g	59000	
		1.0	Snow′		18.1	40	3.0	w|b|p	37000	
		4.0	c		19.1	33	3.0	w o cor	35000	Leak—broken glass.
		5.0	c		20.1	30	3.0	cor	35000	
		6.0	c		21.1	29	3.0	cor	35000	
	Feb. 2	9.7	f	W.	20.1	11	4.2	g b p	100000	
		11.7	f		20.1	16	4.1	Do.	100000	
		1.8	f′	S.	20.1	20	4.1	g′ b p	100000	
		4.0	c	S. W.	20.1	21	4.2	w r g	85000	
		6.5	c		20.1	—	—	—	—	
	Feb. 3	9.5	f	W.	21.1	22	4.1	w o g	80000	
		12.7	f		24.1	24	4.1	Do.	80000	After repairs.
		3.7	f		21.1	23	3.5	w c g	55000	
		6.2	f		21.1	22	3.4	wp cor	51000	
	Feb. 4	9.7	f	W.	20.1	18	3.9	w r g	70000	
		12.0	f		19.1	21	4.4	w br bg	95000	Repeated same.
		6.0	f		21.1	18	3.9	w r g	70000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1904	Feb. 5	9.6	f	W.	—	21	3.6	w r g	59000	
		12.4	f		19.1	25	3.9	w r g	70000	
		4.0	f		19.1	25	3.7	w r g	64000	
		6.1	f		19.1	24	4.2	w y g′	86000	
	Feb. 6	9.6	c Snow		20.1	29	3.1	w br cor	38000	
		11.9	c		19.1	32	3.2	Do.	43000	
		12.9	c		20.1	31	3.3	Do.	45000	
		3.5	c R′		20.1	29	2.8	gbp	28000	
		6.0	c		20.1	30	2.8	Do.	28000	
	Feb. 7	10.0	c		21.1	39	3.6	w r g	57000	
		12.5	c Fog		21.1	46	2.9	g b p	31000	
		5.2	c	W.	23.1	48	2.8	g b p	28000	Apparatus re-
		6.2	c		23.1	50	2.8	Do.	28000	paired.
	Feb. 8	9.4	f	W.	22.1	24	3.7	w r g	64000	
		11.9	f		22.1	26	4.3	w o bg	90000	
		12.7	f		21.1	26	4.3	y′ o bg	90000	
		3.4	f		22.1	24	4.3	y′ o bg	90000	
		6.2	f		22.1	19	3.6	w r g	57000	
	Feb. 9	9.3	f	N.W.	20.1	10	3.9 4.4	w r g w o g	70000	
		12.0	f		19.1	14	4.4	w o bg	95000	
		4.4	f		20.1	15	3.6	w r g	57000	
		6.3	f		19.1	14	3.6	Do.	57000	
	Feb. 10	9.3	f	W.	18.1	9	4.1	g b p	100000	
		11.7	f		18.1	19	4.1	Do.	100000	40 *
		3.2	f		19.1	—	4.1	Do.	100000	41 *
		4.8	f		20.1	25	4.4	w o g	95000	42 *
		6.2	f		20.1	26	3.6	w r g	57000	
	Feb. 11	9.8	f	N.W.	19.1	15	4.2	w o bg	85000	
		12.6	f		18.1	21	3.8	w r g	66000	
		3.4	f		19.1	23	3.1	w|b|r	40000	43
		3.9	c′		19.1	—	3.1	w br cor	40000	44
		4.6	c		19.1	26	3.0	w|b|r	35000	45
		5.8	c		20.1	23	3.7	w r g	62000	46
	Feb. 12	9.5	f	N.	19.1	17	4.0	w r g	75000	
		11.7	f		19.1	24	4.4	w o g	95000	47
		12.7	c′		19.1	—	3.7	w r g	64000	48
		3.8	c		20.1	27	4.2	g b p	100000	49
		4.5	c′		20.1	28	4.2	g′ b p	100000	50
		6.0	f		21.1	27	4.1	w r g	80000	
	Feb. 13	9.6	f	N.	20.1	29	4.1	g b p	100000	
		10.0	f		—	—	4.1	Do.	100000	
		1.2	c		20.1	33	4.4	w o g	95000	
		4.2	c		20.1	31	3.7	w r g	62000	Repeated same.
		6.0	c		20.1	32	4.1	w o g	80000	
	Feb. 14	10.5	c	N.	21.1	28	3.1	w br b|r	38000	
		1.0	c		21.1	31	2.9	w o g	31000	
		5.4	Snow		21.1	30	3.0	cor	35000	
		6.5	Snow		21.1	28	2.8	w r′ g	28000	
	Feb. 15	9.6	Snow	N.W.	21.1	29	4.1 4.1	g b p w o g	100000	

* These numbers refer to photographic slides of the fog particles.

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1904	Feb. 15	11.5	c		21.1	31	3.0	g′ b p	35000	
		3.5	f		21.1	30	3.0	g′ b p	35000	
		6.0	f		23.1	22	3.5	w r g	53000	
	Feb. 16	10.0	f	W.	19.1	6	4.1	g b p	100000	
		12.4	f		20.1	9	4.2	g b p	100000	
		1.3	f		20.1	9	4.2	Do.	100000	
		4.2	f		19.1	9	4.3	w yo bg	93000	
		5.9	f		—	8	3.6	w c g	57000	Cube apparatus.
		6.2	f		—	—	3.6 3.6	wc g wc g	57000	" "
	Feb. 17	9.5	f	W.	—	12	3.9	w r g	70000	" "
		11.6	f		—	18	4.2	w o bg	85000	" "
		12.6	f		—	19	3.9	w r g	73000	" "
		6.2	f		—	18	3.3	w br cor	45000	" "
	Feb. 18	9.8	f	N.W.	—	18	4.2	gy br b′	88000	" "
		12.1	f		—	25	4.1	w o g	83000	" "
		4.1	c		—	30	3.6	w c g	57000	" "
		4.7	c		20.1	29	3.8	w r g	66000	Long apparatus.
		6.2	c		21.1	28	3.8	w rg	66000	
	Feb. 19	9.8	cSnow′	S. W.	20.1	26	4.0	w o g	75000	Repeated same.
		11.3	c		20.1	27	3.9 4.0	w o g w o g	73000	
		11.7	c		20.1	—	4.0	w o g	78000	Cock.
		12.3	c		20.1	28	3.9	w r g	70000	
		12.5	c		—	—	3.8	w c g	66000	
		12.8	Snow		20.1	27	4.0	w y g	78000	Fl.
		1.0	Do.		20.1	—	3.9	w o g	70000	
		4.6	Do.	W.	21.1	—	3.1	w br b|r	38000	Fl.
		5.2	Do.		21.1	26	3.7	w r g	62000	
		5.5	Do.		21.1	—	3.6	w r cor	58000	Ck.
		5.8	Do.		21.1	—	3.6	w p cor	57000	
	Feb. 20	9.7	f	N.W.	20.1	23	4.1	gbp	100000	Repeated same.
		12.4	f		20.1	31	4.3	w o bg	93000	
		1.0	f		20.1	33	4.3	w y g	90000	
		3.4	f		—	36	3.4	w br cor	49000	
		4.7	f		21.1	35	3.4	w br cor	49000	Fl.[1]
		6.2	f		22.1	34	4.3	w o bg	90000	
		6.5	f		22.1	—	4.2	w o g	85000	
	Feb. 21	10.4	f	N.W.	20.1	29	3.9 4.0	w r g w o g	73000	Fl.
		10.8			20.1	31	4.1	w o g	80000	Ck.
		11.8			21.1	33	3.7	w rg	62000	Ck.
		12.0			21.1	—	3.8	w rg	66000	Fl.
		12.2			21.1	—	3.4	w br cor	51000	Fl.
		1.2			21.1	36	3.1	w|b|p	38000	Fl.
		5.4	f		22.1	35	3.1	w br b|r	40000	Fl.
		6.3	f		23.1	35	3.1	w b′ p	38000	Fl.
		6.5	f		23.1	—	3.1	w b′ p	38000	Ck.
	Feb. 22	10.0	R′	S. W.	22.1	49	3.0	g′|b′|p	35000	
		1.0	R′		23.1	49	3.2	wp cor	42000	
		3.2	c		23.1	43	2.4	cor	17000	

[1] Fl refers to the instantaneous valve (Chap. VI, § 33); Ck., to a half-inch plug cock.

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1904	Feb. 22	6.0	f		23.1	38	2.7	w r cor	25000	
	Feb. 23	9.9	f		20.1	36	4.3	g′ br bg	90000	
		11.5	f		20.1	41	4.1	w o g	83000	
		12.5	f		20.1	40	4.4	y′ o bg	95000	
		4.9	f		21.1	40	3.5	wp cor	53000	
		6.2	f		21.1	40	3.1	w|b|p	40000	
	Feb. 24	9.5	c Snow	S. E.	22.1	36	2.8	w r g	28000	
		12.0	Snow	N. E.	—	38	2.9	w o g	31000	
		1.2	Do.		—	37	3.4	wp cor	51000	
		3.4	c	N.	20.1	37	3.0	w o|g	36000	
		6.0	c		—	35	3.0	w o cor	35000	
	Feb. 25	9.8	f	W.	19.1	16	4.1	g′ o bg	80000	
		12.1	f		19.1	18	4.3	y′ o g′	90000	
		12.8	f		19.1	—	4.1	g b p	100000	
		3.8	f		19.1	19	3.7	w r g	62000	
		6.3	f		20.1	16	3.4	w c g	49000	Repeated same.
	Feb. 26	11.7	f		19.1	32	4.1	w or g	80000	
		1.0	f		19.1	24	4.1	w r g	80000	
		3.5	f		19.1	25	3.2	g br b|p	42000	
		5.0	f		19.1	25	3.5	wp cor	53000	
	Feb. 28	10.5	f	S.	20.1	32	2.9	g′|b p	33000	
		1.0	c		21.1	35	2.9	g′|b p	31000	
		5.0	R′	S.	21.1	39	3.2	w|b|r	44000	
		6.3	R		22.1	40	3.3	wp cor	45000	
	Feb. 29	9.5	c	N. E.	22.1	38	2.8	w r|g	28000	
		11.5	c		22.1	41	2.9	w o cor	33000	
		2.3	c		22.1	37	2.5	w br cor	21000	
		6.4	c		23.1	33	2.4	cor	17000	
	Mar. 1	9.8	c Snow		22.1	35	2.5	wbr cor	20000	
		12.7	c	E.	22.1	37	2.8	w r cor	28000	
		3.7	c		22.1	38	3.2	w br b|r	42000	
		6.0	c		22.1	36	2.7	w r g	26000	
	Mar. 2	9.6	f	N. E.	—	35	3.2	w o cor	15000	
		1.2	f	S.	21.1	40	3.7	w c|g	62000	
		5.1	f		21.1	35	{ 3.0 3.1	g′|b|p w br b p }	36000	
	Mar. 3	9.5	R′	S.	22.1	44	3.0	g′|b p	35000	
		12.0	R		22.1	46	2.9	g′|b p	31000	
		2.7	R′ Fog		23.1	48	3.5	w r|g	53000	
		4.2	R′ Fog		23.1	48	2.8	w o|g	28000	
		5.5			—	—	3.0	w o|g	36000	
	Mar. 4	9.8	f	N.W.	19.1	20	4.2	g b p	100000	
		12.0	f		20.1	25	4.3	y′ o gb	90000	
		1.3	f		21.1	26	4.4	Do.	95000	
		3.7	f		20.1	25	4.1	y o g	83000	
		5.8	f		21.1	22	4.1	y′ o g	83000	
	Mar. 5	9.2	f	N.	20.1	17	4.1	w ro g	83000	
		12.5	f		22.1	27	3.2	w|b|p	42000	
		3.6	f		21.1	27	2.9	w o g	31000	
		5.3	f	S.	20.1	26	{ 3.0 2.9	g b p w o r	35000 31000 }	
	Mar. 6	9.8	c	S. E.	20.1	32	3.5	w r|g	53000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1904	Mar. 6	12.1	c	S.	21.1	34	3.0	w o	35000	
		4.0	c′		21.1	35	2.6	w r cor	22000	
		6.2	c′		21.1	23	3.2	w br cor	44000	
	Mar. 7	9.8	c	S.	22.1	44	3.2	w br cor	44000	
		12.1	R′		21.1	46	3.7	w c g	64000	
		4.6	R		22.1	44	2.7	wr cor	26000	
		6.0	R!		22.1	46	2.5	cor	20000	
	Mar. 8	10.0	f′	W.	21.1	51	3.1	wbr cor	38000	
		12.6	f′		—	55	3.0	Do.	35000	
		6.1	f		22.1	43	2.5	cor	21000	
	Mar. 9	10.7	f	W.	22.1	40	4.0	w ro g	75000	
		11.9	f		19.1	35	3.9	w r g	70000	
		3.3	f		19.1	33	3.3	w br cor	47000	
		5.5	f		20.1	—	3.2	Do.	42000	
	Mar. 10	10.0	f	W.	18.1	27	4.1	g′|b′|r′	100000	
		11.5	f		18.1	30	3.9	w r g	70000	Cold wave.
		12.5	f		18.1	32	3.8	Do.	68000	
		5.8	f		19.1	31	3.4	w br cor	49000	
	Mar. 11	9.7	c	N.W.	20.1	34	2.8	cor	30000	
		11.4	c		20.1	34	2.5	w br cor	20000	
		3.8	Snow		20.1	31	2.6	w r cor	23000	
		6.6	c		20.1	30	2.9	w br cor	33000	
	Mar. 12	10.4	f	N.W.	20.1	31	4.1	g b p	100000	
		5.2	f′		21.1	38	3.2	w br B|p	42000	
		6.2	f		21.1	36	3.2	Do.	42000	
	Mar. 13	10.6	f	N.	21.1	33	3.5	w c|g	53000	
		12.3	f		20.1	35	3.5	Do.	53000	
		4.4	f		21.1	37	3.0	g′ B p	36000	
		6.5	f		21.1	34	3.0	w b p	35000	
	Mar. 14	11.2	f	N.W.	20.1	37	3.9	w r g	73000	
		12.8	f		21.1	40	3.8	w r g	68000	
		3.6	c		21.1	37	4.1? / 3.8	Do.? / w rg	70000	
		5.9	c′		22.1	35	4.1	w o g	80000	
	Mar. 15	11.0	Snow	N.	21.1	35	2.9	w r g	31000	
		12.0	Do.		21.1	37	2.9	g b p	31000	
		3.5	Do.		—	38	2.9	g b p	33000	
		6.3	c		21.1	36	2.9	Do.	31000	
	Mar. 16	9.5	f		22.1	37	3.6	w r g	59000	
		12.1	f		21.1	38	3.8	w r g	68000	
		5.0	f		21.1	35	3.0	g′|b|p	35000	
		6.3	f		22.1	33	3.0	Do.	35000	
	Mar. 17	9.8	f	N.W.	21.1	30	4.1	g b p mixed	100000	
		11.0	f		21.1	33	4.1	w o b′	83000	
		1.0	f		21.1	37	3.7	w c g	64000	
		3.4	f		21.1	40	3.0	g′ cor	35000	
		5.6	f		21.1	35	3.4	wp cor	49000	
	Mar. 18	10.1	Snow	S. E.	22.1	35	2.9	w o|g	31000	
		12.7	Snow′		22.1	39	2.8	w r|g	30000	
		3.6	R′		22.1	41	3.4	wp cor	49000	
		5.0	R		22.1	39	3.1	w br B r	40000	
		6.5	R′		23.1	37	2.8	w′ B p	30000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture s.	Corona Colors.	Number n	Remarks.
1904	Mar. 19	10.5	f	W.	22.1	44	2.9	g|b|p	33000	
		1.0	f		22.1	48	{ 3.6	w r g	57000	
							{ 3.1	g|B|p	38000	
		3.7	f		22.1	48	3.5	w r|g	53000	
		6.3	f		23.1	44	3.0	w o cor	35000	
	Mar. 20	9.4	f	W.	22.1	49	3.0	wo cor	35000	
		12.3	f		21.1	48	2.8	w r g	30000	
		6.2	f		20.1	38	2.4	cor	17500	
	Mar. 21	9.8	f	N.	17.1	39	4.0	g′ b p	100000	
		10.6	f		17.1	—	4.1	g b p	100000	
		1.0	f		18.1	45	4.0	Do.	100000	
		5.4	f		18.1	45	3.0	w|b|r	35000	
		6.5			18.1	40	3.0	Do.	35000	
	Mar. 22	10.2	c	S.	—	42	2.9	w o cor	33000	
		12.6	c R′		21.1	42	3.0	g′|B|p	35000	
		3.8	c R′		20.1	41	2.8	g′ b p	30000	
		6.1	R		21.1	44	2.8	w r g	30000	
	Mar. 23	10.3	c to f	N.W.	21.1	53	2.8	w o g	30000	
		12.4	f		22.1	59	4.3	w o bg	90000	
		1.0	f		22.1	59	3.8	w c g	66000	
		4.3	f′		22.1	55	3.0	wo cor	35000	
		6.3	f′		22.1	50	2.9	g′|B|p	31000	
	Mar. 24	9.5	f	N.W.	19.1	49	4.2	w o g	85000	
		9.8	f		19.1	—	4.3	Do.	90000	
		1.2	f		20.1	57	3.5	w c g	53000	
		3.0	f		20.1	59	3.6	w rg	59000	
		6.4	f	S.	20.1	45	3.6	w r g	59000	
	Mar. 25	9.6	c	S.	18.1	51	4.1	w r g	80000	
		10.1	c		—	—	3.5	wp cor	53000	
		1.0	c		20.1	54	3.3	Do.	45000	
		5.5	c		22.1	57	2.8	w r g	28000	Repeated same.
		6.5	c		22.1	57	2.8	w r g	28000	
	Mar. 26	9.6	c′	S. W.	21.1	61	3.0	g|B|r	35000	
		11.1	c′		21.1	—	3.5	w r g	35000	
		12.1	c′		22.1	58	3.1	w|b|r	38000	
		4.7	c′		21.1	58	2.1	cor	13000	
		6.4	f		21.1	54	2.2	cor	13000	
	Mar. 27	10.5	c	E.	18.1	40	3.3	wp cor	45000	
		12.2	c		18.1	41	2.9	g′ b p	31000	
		5.0	c	E.	17.1	38	2.3	wy cor	16000	Repeated $s = 2.9$.
		6.4	c		17.1	36	2.7	w r|g	25000	
	Mar. 28	10.7	c	N.W.	16.1	38	3.6	w p|g	57000	
		12.7	c	S.	16.1	41	2.9	wo cor	31000	
		3.5	c		17.1	39	2.9	g′|B|p	31000	
		6.5	c		17.1	36	2.8	w b p	28000	
	Mar. 29	10.2	f	N.W.	18.1	37	4.1	gy o bg	80000	
		1.4	f		18.1	42	3.4	wp cor	49000	
		3.2	f	W.	18.1	44	3.0	w|B|r	35000	
		6.3	f		20.1	42	3.5	w c g	55000	
	Mar. 30	9.1	f	N.W.	21.1	42	2.8	g′ B p	28000	
		12.5	f	S.	20.1	48	3.8	w r g	68000	
		4.0	f		20.1	44	2.9	g′ B p	33000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1904	Mar. 30	6.0	f		20.1	41	3.2	wp cor	42000	
	Mar. 31	9.5	f H	S.	18.1	42	2.9	wo g	31000	
		11.4	c′		18.1	49	3.5	wp cor	55000	
		3.7	R′		19.1	4–	2.9	w o g	31000	
		6.5	R		20.1	40	2.4	w br cor	17000	
	Apr. 1	9.5	R	E.	20.1	41	2.4	wbr cor	19000	
		12.7	R		20.1	41	2.6	Do.	22000	
		6.8	R′		22.1	46	3.0	w B p	35000	
	Apr. 2	9.3	f		21.1	47	2.9	g′ b p	31000	
		11.5	c′	W.	21.1	55	3.0	w o cor	35000	
		3.4	c′		22.1	54	2.9	w o g	33000	
		6.3	c′		21.1	48	2.8	w|b|p	29000	
	Apr. 3	10.3	c′	N.W.	18.1	43	3.7	w r g	64000	
		1.3	c		18.1	45	3.7	Do.	61000	
		4.7	c		18.1	41	2.9	g b p	33000	
		6.3	c		18.1	37	4.1	w o g	80000	
		6.5	c		18.1	37	3.7	w c g	61000	
	Apr. 4	9.5	f	N.	19.1	37	4.2	y′ o bg	85000	
		12.7	f		18.1	46	3.8	w rg	66000	
		3.5	f	W.	19.1	51	3.2	w p cor	44000	
		5.4	f		20.1	50	3.2 3.0	w|b|r w|b|p	42000	
	Apr. 5	9.0	f	W.	18.1	48	4.1	g b p	80000	
		12.5	f		19.1	—	3.6	w r g	57000	
		6.0	f	S.	19.1	53	3.8	w c g	66000	
	Apr. 6	9.7	f	E.	18.1	56	4.2	y br bg	83000	6.5/82 [1]
		11.4	f	S.	—	60	4.1	w o g	80000	5.5/74
		3.5	f		18.1	58	3.5	wp cor	53000	
		3.9	f		18.1	—	3.1	wbrcor	38000	5/37
		6.6	f		18.1	50	2.9	w|b|p	33000	5/44
	Apr. 7	9.5	R	S.	18.1	51	3.0	w y cor	35000	5/40
		1.0	R′		18.1	53	3.2	w|B|r	42000	5/47
		4.4	f		19.1	60	2.3	wy cor	15000	5/30
		5.5	f		19.1	59	2.7	wc g	25000	5/35
	Apr. 9	8.0	R		21.1	46	2.8	w r g	28000	Night.
		9.2	R		21.1	50	2.8	Do.	28000	
	Apr. 10	10.7	f	S.	21.1	55	2.2	wbr cor	14000	5/25
		1.5	f		21.1	56	2.8	w o g	28000	5/40
		5.4	f		20.1	60	2.7	w rg	25000	5/35
		6.7	f		21.1	57	2.2	cor	13500	5/32
	Apr. 11	9.2	c R′	N.W.	19.1	50	3.3	wp cor	45000	5/53
		12.4	R		19.1	53	3.0	w|b|p	35000	5/49
		4.3	f		20.1	53	2.3	cor	16000	5/22
		5.6	c′		20.1	52	2.9	cor	31000	5/46
		6.4	c′		20.1	51	2.8	w b p	28000	5/45
	Apr. 12	9.3	R	S.	19.1	46	2.8	w o g	28000	5/37
		11.7	R		19.1	52	3.0	w|b|r	35000	5/51
		5.0	c Sun		20.1	54	3.0	g′ b p	37000	5/49
		6.1	c′		20.1	54	3.8	w r g	66000	5/62
	Apr. 13	9.3	c′	W.	18.1	45	3.0	g′ b p	35000	4/38
		12.5	c′		18.1	48	2.9	w r g	31000	5/44

[1] Subsidence data, showing a fall of fog level of 6.5 cm. in 82 sec., 5.5 cm. in 74 sec., 5 cm. in 37 sec., etc.

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1904	Apr. 13	6.4	c′		19.1	44	3.0	w br cor	37000	
		8.3	f		18.1	40	3.4	w p cor	51000	5/55 Night.
		10.1	f		18.1	36	3.0	w o g	33000	5/41
	Apr. 14	9.0	c	W.	17.1	39	2.8	w r g	28000	5/36
		1.0	R-Sn.		17.1	37	2.8	w o g	30000	5/46
		5.5	f		17.1	41	2.9	g b p	33000	5/42
		6.5	f		18.1	39	3.0	g′|b|p	35000	
	Apr. 15	9.4	f	W.	16.1	42	3.1	g|b|p	38000	5/48
		3.5	c′	S.	16.1	49	3.0	w o cor	35000	
		6.4	c		18.1	45	3.5	wp cor	53000	
	Apr. 16	9.5	Sn.-R	N. E.	—	38	3.1	wp cor	40000	5/50
		12.0	R′		17.1	38	4.1	g b p	80000	5/74
		12.7	R′		17.1	38	3.6	w c g	59000	
		3.6	c′	N.W.	18.1	42	3.6	w c g	59000	
		6.0	f		18.1	39	2.9	w′|b|r	33000	
	Apr. 17	9.6	f	W.	20.1	40	2.9	g b p	33000	5/50
		11.3	f		20.1	44	3.0	w br cor	36000	5/50
		3.2	f		21.1	50	3.0	Do.	36000	
		5.6	f		21.1	49	2.9	w|b|r	31000	5/48
	Apr. 18	9.4	f	S.	22.1	49	2.9	w o cor	31000	5/42
		12.7	f		21.1	51	2.8	wog	30000	5/36
		3.4	f′		—	51	2.8	w r g	28000	5/35
	Apr. 19	9.7	f	S.	19.1	54	3.0	wp cor	35000	5/45
		12.3	c′		19.1	59	2.9	Do.	33000	
		3.1	c′ R′	S. W.	19.1	59	2.9	w r g	33000	5/35
	Apr. 20	9.8	c′Snow		16.1	35	3.7	w rg	61000	
		12.9	c		16.1	39	3.1	w|b|r	38000	
		3.7	c		17.1	41	3.0	g b r	37000	5/46
		6.3	c		17.1	40	3.0	v′ br cor	37000	5/39
	Apr. 21	9.7	f	N.W.	18.1	50	4.0	g b p	100000	5/83
		11.8	f		18.1	54	4.2	g b p	100000	5/78
		3.6	f		18.1	54	4.0	g b p	100000	5/72
	Apr. 22	9.5	f	N.W.	17.1	51	4.0	w r g	75000	5/58
		12.7	f		18.1	50	4.2	w y g	85000	5/63
		5.0	f	S.	19.1	49	2.9	w y cor	31000	5/39
		6.3	f		19.1	47	2.9	w o cor	31000	5/33
	Apr. 23	9.0	f	S.	16.1	51	4.0	w ro g	78000	5/66
		12.1	f		17.1	57	3.2	wp cor	42000	5/51
		4.4	f		17.1	50	3.0	w br cor	35000	5/42
		6.3	f		18.1	46	2.9	cor	31000	5/42
	Apr. 24	10.0	f	S.	20.1	51	3.3	wp cor	47000	5/55
		12.5	f		21.1	54	3.0	w b p	35000	5/52
		5.5	f		21.1	50	2.9	w rg	31000	5/38
	Apr. 25	9.3	f R′	S.	22.1	54	2.7	w rg	27000	5/36
		12.7	f′		21.1	62	3.3	wp cor	45000	5/51
		3.6	f′		21.1	62	2.9	wrg	33000	5/38
		6.3	f′		21.1	58	3.0	cor	35000	5/43
	Apr. 26	9.5	f′	N.W.	21.1	57	3.6	wp cor	57000	5/55
		12.3	f	S.	—	61	4.0	wrg	75000	5/64
		5.5	f		20.1	56	3.0	g b p	35000	5/48
	Apr. 27	9.3	R	N. E.	20.1	45	1.8	wy cor	7500	5/23
		12.3	R		20.1	46	2.0	wr cor	11000	5/25

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1904	Apr. 27	3.4	R		20.1	45	2.0	w r cor	10000	5/25
		6.0	R		20.1	42	1.9	cor	8500	5/24
	Apr. 28	9.4	R	N. E.	22.1	46	2.4	cor	17000	5/32
		11.5	R		21.1	48	2.1	cor	12000	5/24
		4.0	R		21.1	52	2.1	cor	12000	5/27
		4.7	R		22.1	—	1.9	cor	8500	2/5 2/10 2/7 [1]
		4.9	R		—	—	1.9	cor	8500	2/15 2/6 2/6
		5.5	R		21.1	53	—	cor	—	2/13 2/11 2/6
		5.7	R		—	—	1.9	wrcor	8500	2/16 2/9 2/5
		5.9	R		—	—	1.9	—	8500	2/16 2/12 —
	Apr. 29	8.8	R′		22.1	51	3.7	w r g	61000	2/18 2/23 2/22
		9.3	R′		—	—	3.0	w|b|p	35000	2/20 2/18 2/16
		9.7	c		—	—	3.0	w ro g	35000	2/20 2/15 2/12
		11.5	c		22.1	55	2.8	w r g	30000	2/17 2/12 2/10
		3.5	R′		22.1	57	2.2	wp cor	13000	2/13 2/8 2/5
		6.1	c		22.1	57	3.0	wbr cor	35000	
	Apr. 30	10.0	c′	N.W.	21.1	63	3.0	w|b|p	37000	2/19 2/14 2/24
		11.0	c′ (S)		21.1	63	3.0	w r g	37000	2/20 2/14 2/12
		2.3	R	S. E.	21.1	64	2.9	w r g	33000	2/15 2/14 2/11
		6.0	c′ (S)		21.1	62	3.0	w b p	35000	2/23 2/15 2/17
	May 1	9.6	f to c	N. E.	21.1	59	1.9	cor	9000	2/13 2/8 2/6
		12.0	c		21.1	62	2.7	w r g	25000	
		3.1	c′		21.1	64	2.5	cor	21000	
		6.4	c′		21.1	55	2.3	cor	16000	
	May 2	9.0	f	N.W.	18.1	59	3.4	wp cor	49000	5/51
		12.3	f	N. E.	19.1	63	3.0	cor	36000	
		3.3	f	E.	19.1	62	2.8	w rg	28000	
		5.4	f		19.1	60	3.1	w|B|p	38000	
	May 3	9.2	f	N.W.	18.1	57	4.1	g b p	100000	Repeated same.
		11.2	f	S.	18.1	63	3.8	w r g	68000	
		5.4	f		17.1	54	2.8	w r g	28000	
	May 4	9.3	f	S.	17.1	61	4.0	y o bg	78000	
		11.7	f		17.1	65	3.8	w c g	66000	
		3.1	f		18.1	74	3.1	w br cor	40000	
		6.3	f		18.1	67	3.1	g|b p	38000	
	May 5	9.2	f	W.	18.1	72	4.0	w y bg	78000	
		12.3	f		20.1	79	2.9	w o cor	31000	
		3.4	f		22.1	82	2.4	cor	17000	
	May 6	9.4	f	N. E.	18.1	67	2.8	w br|g	29000	
		12.2	f		19.1	70	2.9	w br cor	31000	
		3.3	f		19.1	68	3.0	w o|g	35000	
		6.3	f	S.	18.1	61	3.0	g|b p	35000	
		8.8	f		18.1	53	3.0	w b p	35000	Night.
		9.7	f		18.1	52	2.7	w rg cor	25000	
	May 7	9.3	f Fog	S. W.	17.1	59	2.6	wbr cor	23000	
		11.9	f	S.	18.1	67	3.1	w|b|r	38000	
		4.0	f		19.1	74	2.8	w o cor	29000	
		5.2	f		19.1	71	2.6	w br cor	22000	
	May 8	12.0	f	S. W.	19.1	74	3.0	g′ br cor	35000	
		4.0	f		20.1	74	2.9	w y|g	31000	
		6.0	f		20.1	67	2.1	cor	12000	

[1] Subsidence over consecutive distances of 2 cm. each.

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture s.	Corona Colors.	Number n.	Remarks.
1904	May 9	9.5	R	E.	19.1	63	1.8	cor	7000	
		12.3	R		19.1	65	2.0	cor	10000	
		3.6	R′		20.1	66	2.1	w r cor	12000	
	May 10	9.4	f	W.	19.1	70	4.3	y′ br bg′	90000	
		9.8	f		19.1	—	4.2	y o bg	88000	2/36 2/24
		12.5	f		20.1	74	3.0	cor	35000	
		3.5	f	S.	20.1	72	2.9	w|b|r	31000	
		6.2	c		20.1	71	2.9	Do.	33000	
	May 11	9.3	c	N.W.	20.1	64	2.2	w r g	13000	Rain at night.
		12.6	c	S.	20.1	68	3.4	wp cor	49000	
		4.5	f′ f		20.1	70	3.0	w|b|r	36000	
		6.3	c		20.1	69	2.9	g′ b p	31000	
	May 12	9.4	f′	N.W.	19.1	63	2.4	cor	19000	
		3.2	f	N. E.	19.1	67	2.6	cor	22000	
		5.6	f	S.	19.1	64	3.0	w|b|r	35000	
	May 13	9.2	f	N.W.	19.1	69	3.5	w r g	53000	
		4.7	f		19.1	72	2.0	cor	11000	Repeated $s = 2.1$.
		6.4	f		19.1	66	1.9	cor	8000	
	May 14	9.0	c′ Fog		19.1	63	2.1	cor	12000	
		12.5	c		19.1	66	1.9	cor	8000	
		6.2	c′		19.1	60	1.8	cor	7000	
	May 15	9.5	c	N. E.	18 1	58	1.8	cor	7000	
		12.5	c		18.1	62	2.0	cor	10000	
		6.2	R		19.1	55	2.0	cor	10000	
	May 16	9.5	c′ (S)		18.1	60	3.2	wp cor	43000	Rain at night.
		12.1	c′		18.1	62	3.0	w o g	35000	
		3.3	c′ R′		18.1	59	2.9	w o g	33000	
		6.0	f		17.1	60	3.0	w br b|r	35000	
	May 17	9.3	c	S. W.	17.1	58	3.3	w|b|r	45000	
		12.5	c		17.1	63	3.2	Do.	42000	
		2.3	c′		17.1	65	3.0	w o g	35000	
		6.1	c		17.1	62	3.0	w|b r	35000	
	May 18	9.2	c R′	N. E.	17.1	63	1.9	cor	8000	
		12.5	R′		20.1	63	1.9	cor	8500	
		5.5	c		18.1	58	1.9	cor	8500	
	May 19	9.5	c	N.	17.1	55	2.9	w r g	31000	
		11.9	c		18.1	59	1.9	cor	8000	
		3.0	R		18.1	56	2.3	cor	15000	
		5.6	R		19.1	55	2.8	w r g	28000	
	May 20	9.1	c	S. W.	18.1	63	2.8	w r g	28000	
		12.5	c′ (S)		18.1	69	3.2	wp cor	42000	
		3.0	R′	W.	18.1	61	2.8	w r g	30000	
		6.1	f	S.	—	62	2.8	w r g	28000	
	May 21	9.5	f	N.W.	18.1	67	3.8	y′ o g′	66000	
		12.7	f		19.1	73	3.0	w r g ?	35000	
		4.8	f	S.	20.1	69	2.9	w o g	31000	
		6.0	f		—	68	3.2	w p cor	42000	
	May 22	9.8	f	S.	19.1	68	2.4	cor	17500	
		10.8	f		19.1	70	2.4	cor *b*	18500	
		12.3	f		19.1	71	2.2	cor	13500	
	May 23	9.7	f	S.	19.1	67	3.0	g b|p	36500	
		12.3	f		19.1	68	3.0	Do.	35000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture s.	Corona Colors.	Number n.	Remarks.
1904	May 23	6.3	f		19.1	66	2.9	w r g	31000	
	May 24	9.3	c′	S. W.	19.1	69	2.9	w|b|p	31000	Rain at night.
		12.5	f		20.1	75	2.9	w o g	31000	
		3.2	f		20.1	76	2.7	w r g	25000	
	May 25	9.3	f	N.W.	20.1	75	3.5	w c g	53000	
		12.7	f		20.1	78	2.8	w r g	30000	
		3.4	f		20.1	73	2.3	cor	15000	
		6.3	f		21.1	70	2.3	cor	16000	
	May 26	9.3	f	S.	21.1	78	2.9	cor b	31000	
		12.4	f′		22.1	78	2.8	w r g	28000	
		6.4	f		22.1	74	2.3	wycor	15000	
	May 27	9.8	f′	S. W.	21.1	76	2.9	w o g	31000	Rain at night.
		12.0	f		22.1	82	3.5	wp cor	53000	
		3.2	R		23.1	71	3.0	g|b|p	36000	
		5.5	f		22.1	71	2.4	cor	17000	
	May 28	9.5	f	W.	20.1	68	4.1	w o bg	80000	
		9.7	f		20.1	—	3.3	g|b|p	45000	Repeated.
		1.0	f		20.1	73	3.1	w y′ g	38000	
		5.7	f		22.1	74	3.0	w|b|r	35000	
	May 29	9.6	f	S.	21.1	71	3.5	wp cor	53000	
		10.1	f		21.1	72	3.4	Do.	50000	
		10.8	f		21.1	74	3.4	w r g	49000	
		12.0	f		22.1	74	3.2	wp cor	42000	
		4.5	f	S. W.	22.1	75	1.8	cor	7000	
		6.4	f		23.1	70	2.8	w r g	28000	
	May 30	9.5	c′		21.1	72	2.4	cor	17000	Repeated same.
		1.0	c		22.1	74	2.4	cor	19000	
		2.5	c		22.1	73	1.9	cor	8500	
		6.4	c		22.1	69	2.4	cor	17000	
	May 31	9.5	c	N. E.	20.1	65	3.0	w r g	35000	Rain at night.
		12.3	c′ (S)		20.1	70	2.7	w rg	26000	New apparatus same.
		3.5	f′ (S)		20.1	71	2.7	w r g	26000	New brass apparatus. Repeated $s=2.8$.
		6.3	f′		—	65	2.1	w r g	12000	
		8.4	f′		21.1	60	2.1	Do.	12000	Night.
	June 1	9.0	c	N. E.	20.1	62	2.8	w|b|p	28000	
		11.5	c		19.1	65	2.4	cor	19000	
		4.5	R		19.1	57	1.9	cor	8500	
		5.8	R		19.1	56	1.8	cor	7000	
	June 2	10.4	c	N.	17.1	57	1.9	cor	8500	
		12.9	c		17.1	60	2.1	w r g	12500	
		4.7	c		18.1	58	1.8	cor	7000	
		6.3	c		18.1	56	1.8	cor	7000	
	June 3	9.8	c	N. E.	18.1	59	2.2	cor	13000	
		10.8	c		18.1	—	2.2	cor	13000	
		11.5	f′ (S)		18.1	67	2.6	w r g	24000	
		12.3	f′		—	—	2.8	w|b|p	28000	
		3.3	f′ (S)		19.1	74	2.8	w r g	28000	
		6.0	f		19.1	70	2.8	wrg	28000	
	June 4	9.5	f	N. E.	19.1	73	2.9	w|b|r	31000	
		12.5	f′		19.1	78	2.3	cor	15000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture s.	Corona Colors.	Number n.	Remarks.
1904	June 4	5.0	f		20.1	72	2.1	w r g	12000	
		6.5	f	S. W.	20.1	67	2.5	w r g	20000	
	June 5	10.5	f	S. W.	19.1	77	2.7	w r g	25000	
		4.0	f		20.1	83	2.4	cor	19000	
	June 6	9.7	c	N. E.	18.1	60	1.5	cor	4000	
		10.5	c		18.1	63	1.5	cor	4500	
		12.0	c		18.1	66	1.9	cor	8500	
		5.0	c		19.1	67	1.8	cor	7500	
	June 7	9.5	c	N.	18.1	62	2.2	cor	13500	Rain heavy at night.
		12.5	R′	S. W.	19.1	70	2.8	w rg	28000	
		3.1	R′		19.1	69	2.9	w r g	31000	
		5.2	f		19.1	68	2.3	w rg	15000	
	June 8	9.9	c	S. E.	20.1	71	1.5	cor	4000	Rain at night.
		11.0	c		20.1	74	1.5	cor	4000	
		12.3	c	E.	20.1	73	1.6	cor	5500	
		5.5	f		20.1	68	1.7	cor	6000	
	June 9	10.0	R′ f	N. E.	19.1	65	2.6	w r g	24000	
		12.0	f′		19.1	—	2.7	Do.	26000	
	June 11	9.6	f	N.	18.1	69	2.6	cor	22000	
		12.1	f		18.1	69	2.1	cor	11500	
		3.6	f	N. E.	18.1	70	1.8	cor	7000	
		6.0	f		18.1	67	1.8	cor	7000	
	June 12	9.5	f		17.1	66	2.2	cor	13000	
		11.7	f	N. E.	17.1	68	2.5	cor	20000	
		3.0	f		17.1	—	1.9	cor	8500	
	June 13	9.4	c	N. E.	17.1	62	2.5	cor	20000	
		3.6	c′		17.1	66	2.7	w r g	25000	
	June 14	10.0	f	S.	17.1	62	3.9	w rg	70000	
		10.3	f		—	—	3.9	w ro g	70000	
		3.3	f		17.1	62	3.0	w|b|p	35000	
		5.6	f		18.1	54	2.6	cor	22000	
	June 15	5.5	f	S.	17.1	67	2.6	w|b|r	22000	
	June 16	10.3	c′	S. W.	17.1	72	3.7	w rg	61000	
		10.5	—		—	—	3.9	g′ b p	71000	Repeated.
		12.4	c′		18.1	77	4.1	g b p	100000	
		3.6	R′		19.1	74	3.2	—	42000	
		6.0	c′		19.1	71	2.8	w|b|r	30000	
	June 17	9.8	f	N. E.	18.1	72	2.7	w rg	25000	Repeated $s=2.6$.
		12.0	f		19.1	76	2.7	w rg	25000	
		3.0	f	S.	19.1	76	2.7	w rg	25000	
		5.5	f		19.1	72	2.8	w|b|r	28000	
	June 18	3.1	f	W.	19.1	74	2.8	w|b|r	28000	
		12.1	f		19.1	79	2.3	cor	15000	
		3.5	f		20.1	82	3.0	w|b|r	35000	Repeated $s=2.4$.
		6.3	f		21.1	79	2.6	w r g	22000	
	June 19	9.5	f	N.W.	20.1	74	3.5	w rg	53000	
		9.8	f		20.1	—	4.2	w o bg	85000	Repeated.
		10.3	f		20.1	—	3.6	w r g	58000	
	June 20	10.1	f	N.W.	20.1	78	3.9	w o g	70000	
		10.8	f		—	80	3.9	w o g	70000	
		12.4	f		21.1	82	3.6	w r g	57000	
		2.6	f	S.	21.1	78	2.3	cor	15000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1904	June 20	5.0	f		22.1	75	2.4	cor	17000	
	June 21	9.8	f′	S. W.	22.1	77	2.8	w o b′	29000	
		10.4	f′		23.1	—	2.9 2.9	w|b|r w r g	31000	Old apparatus.
		2.0	f		23.1	85	2.9	w br cor	33000	
	June 22	9.1	f	W.	23.1	81	2.8	wr cor	30000	
		12.4	f		23.1	85	2.9	w o g	31000	
		2.5	c R′		23.1	80	2.8	w o g	28000	
		5.5	f		24.1	78	2.6	cor	22000	
	June 23	10.2	f	N. E.	22.1	71	2.5	cor	20000	
		12.5	f		22.1	74	2.7	wr cor	25000	
		3.4	f		—	75	2.7	wr cor	26000	
		5.5	f		22.1	71	3.0	w y cor	35000	
	June 24	11.0	f	W.	21.1	77	3.0	w obr cor	36000	
		12.9	f		22.1	79	3.4	wp cor	49000	
		4.6	f		22.1	75	2.8	w r cor	28000	
	June 25	9.0	f	S. W.	22.1	78	3.0	g′ B p	36000	
		12.5	f		24.1	86	3.1	w o g	40000	
		3.3	f		24.1	90 ?	2.6	cor	22000	
		5.8	f		24.1	84	2.0	cor	10000	
	June 26	9.0	f	W.	24.1	87 ?	2.7	w r cor	25000	
		12.7	f		24.1	33.6C.	2.7	wbr cor	25000	
		3.8	R		24.1	80	1.3	cor	2500	Violent thunderstorm.
		4.2	R off		25.1	80	2.8	w r g	28000	
		5.6	f		—	81	2.6	w br cor	22000	
	June 27	10.5	f	N.W.	23.1	81	3.3	wp cor	45000	
		11.0	f		—	—	3.1	w br cor	38000	
		12.9	f			84	3.0	w b p	36000	
		3.8	f		—	84	2.7	w br cor	25000	
		5.5	f		24.1	81	2.2	cor	13000	
	June 28	9.2	c′	E.	23.1	73	2.3	cor	16000	
		12.0	c′		23.1	81	2.6	cor	22000	
		5.3	c		23.1	74	2.8	w r g	30000	
	June 29	10.3	R′	S. E.	22.1	64	2.2	cor	14000	
		3.2	c	N.	23.1	70	2.3	cor	15000	
		6.0	c		23.1	69	2.2	w r|g	14000	
	June 30	10.1	c R′	S.	—	70	2.4	w br cor	17000	
		12.7	c		24.1	73	2.9	w r g	31000	
		5.8	R	S.	24.1	72	3.0	w b cor	37000	
	July 1	9.0	R		24.1	72	2.3	w r|g	15000	
		10.8	c		24.1	76	2.7	wp cor	25000	
		3.3	c		24.1	75	3.0	w r g	35000	
		5.5	c	S. W.	24.1	74	2.7	cor	25000	
	July 2	9.5	f	S. W.	23.1	75	3.2	wp cor	42000	
		12.3	f		23.1	77	3.0	g′|b|p	35000	
	July 15	11.0	f		24.1	83	3.1	w br b|r	38000	
		6.1	f		24.1	77	2.5	cor	20000	
	July 16	9.7	c	S. W.	25.1	77	2.6	w br cor	22000	
		12.5	c′		25.1	85	3.0	w r g	35000	
		5.8	f		25.1	79	2.0	cor	11000	
	July 17	11.1	f	N.	—	84	1.6	cor	5500	
		12.7	f′		25.1	86	1.6	cor	5500	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture s.	Corona Colors.	Number n.	Remarks.
1904	July 17	2.5	f′		—	—	1.5	cor	4500	
		5.0	f		26.1	85	1.8	cor	7000	
	July 18	9.5	f	N.W.	24.1	84	3.6	w r g	59000	
		10.8	f		25.1	85	3.4	wp cor	51000	
		1.6	f	S.	25.1	89 ?	2.8	w r g	28000	
	July 19	11.3	f	S.	25.1	81	2.3	w o cor	16000	
		12.9	f		26.1	86	2.3	Do.	16000	
		2.4	f		—	87	2.3	Do.	16000	
		5.7	f		26.1	78	2.3	Do.	16000	
	July 20	10.2	f	N.W.	26.1	87	3.0	w ro|g	35000	
		2.0	f	W.	26.1	88	2.7	w br cor	25000	
		5.7	f		25.1	84	2.2	cor	14000	
	July 21	9.6	f	W.	25.1	81	3.0	w r|g	35000	
		12.0	f		25.1	84	3.0	w o g	35000	
		3.2	f		25.1	84	2.3	w r|g	15000	
		5.6	f		25.1	82	2.2	cor	13000	
	July 22	10.0	c′	E.	24.1	77	2.3	w rbr cor	15000	
		12.5	c		24.1	81	1.6	cor	5000	
		4.6	R′		24.1	71	1.6	cor	5500	
		6.0	c		24.1	69	1.8	cor	7500	
	July 23	9.7	R′	N. E.	24.1	66	1.4	cor	3000	Rain at night.
		12.3	c		24.1	64	1.4	cor	3000	
		3.5	c	N.	23.1	66	1.6	cor	5000	
		5.9	c		23.1	63	1.6	cor	5500	
	July 24	12.2	c	N.	—	68	1.4	cor	3000	Repeated $s=1.3$.
		6.0	R		23.1	65	1.2	cor	2000	" $s=1.1$.
	July 25	9.5	c	S.	23.1	72	2.3	cor	15000	
		12.5	f′		23.1	79	2.4	cor	19000	
		6.0	f		—	78	2.6	cor	22000	
	July 26	10.7	c′ R′	S.	23.1	79	3.1	w|b|p	40000	
		12.4	c′		24.1	80	3.1	Do.	38000	
		4.0	f		24.1	80	3.1	Do.	38000	
		6.0	f		24.1	77	2.9	w r g	31000	
	July 27	9.5	c′ R′	W.	24.1	78	3.1	g′|b|p	38000	Rain at night.
		12.1	c′		24.1	80	3.0	w y o g	35000	
		3.4	c′		24.1	82	3.0	Do.	35000	
		6.0	f		24.1	77	2.9	w o g	33000	
	July 28	2.1	c′	S. W	—	83	2.8	w r g	28000	
		6.5	c		25.1	76	2.4	w rcor	17500	
	July 29	10.4	c	W.	25.1	78	2.7	wp cor	25000	
		12.7	f		24.1	83	3.0	w|b|p	35000	
		3.3	f		24.1	82	3.0	w r g	35000	
		5.6	f		25.1	78	2.4	cor	17500	
	July 30	9.7	f	N.	23.1	71	3.8	w r g	66000	
		10.0	f		—	—	3.6	w r g	59000	
		12.6	f		23.6	77	3.1	w o g	40000	
		4.2	f		24.1	74	2.7	wp cor	25000	
		5.7	f		24.1	71	2.6	w br cor	22000	Repeated same.
	July 31	9.4	f′	S. W.	24.1	78	2.2	cor	14500	
		12.1	f		24.1	84	2.0	cor	10000	
		4.0	f		24.1	84	1.5	cor	4000	
		6.0	f		25.1	80	1.5	cor	4000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1904	Aug. 1	9.5	c	S. W.	25.1	82	2.4	cor	17500	
		12.3	c		25.1	84	2.4	cor	17500	
		3.1	c		25.1	85	2.4	cor	17500	
		5.7	c		26.1	81	{ 2.9	w|b|p	31000	
							{ 2.7	w rg	27000	
	Aug. 2	9.4	c	N.	25.1	76	2.2	cor	13500	
		12.9	R′		25.1	76	2.2	w r|g	13500	
		3.0	R		25.1	74	2.8	w r|g	28000	
		3.5	R		—	—	2.4	—	17500	
		6.0	R		26.1	73	2.7	w r g	25000	
	Aug. 3	9.0	f	N.	24.1	76	2.0	cor	10000	
		12.5	c	N.	25.1	79	2.9	cor	31000	
		5.1	c		25.1	76	1.4	cor	3000	
	Aug. 4	10.0	c	N. E.	24.1	70	1.4	cor	3000	Rain at night.
		12.5	c		24.1	73	1.3	cor	2500	
		4.0	f′		24.1	75	1.9	wo cor	8500	
		6.1	f	S.	24.1	71	2.4	cor	17500	
	Aug. 5	9.8	c′	S.	23.1	74	1.8	cor	7000	
		12.4	c′	S.	24.1	74	2.6	cor	24000	
		3.5	c		23.1	73	2.2	cor	13500	
		5.5	c	S.	24.1	71	2.2	w r|g	13500	
	Aug. 6	10.5	c	S.	24.1	74	2.2	cor	13500	
		12.7	f′	S.	24.1	79	2.8	w r g	30000	
		5.4	f	S.	24.1	77	2.1	cor	11500	
	Aug. 7	9.8	f	W.	24.1	80	2.0	cor	10000	
		12.0	f	S. W.	24.1	84	2.2	cor	13500	
		4.7	f	W.	24.1	83	1.9	cor	8500	
		6.0	f		—	80	2.3	cor	15500	
	Aug. 8	10.0	R	S. E.	24.1	73	2.3	cor	15500	
		10.7	R	S. E.	—	—	2.3	Do.	15500	
		12.7	c	S.	24.1	76	2.3	cor	16500	
		3.3	c	W.	24.1	78	2.6	wp cor	23500	
		6.0	c	W.	24.1	75	2.4	cor	19000	
	Aug. 9	9.8	f	N.	23.1	70	3.7	w c g	64000	
		10.5	f		—	71	3.8	Do.	66000	
		12.3	f	N.W.	23.1	73	3.8	Do.	66000	
		3.8	f		23.1	72	2.4	cor	17500	
		6.0	f	S.	23.1	69	3.0	w|b|p	36500	
	Aug. 10	10.0	c	S. E.	23.1	70	3.1	w|b|p	38000	
		12.0	c R′	S. E.	22.1	70	3.1	Do.	38000	
		5.2	c R		23.1	66	1.7	cor	6500	After rain.
		6.5	c		23.1	66	2.1	cor	11600	
	Aug. 11	10.0	c	W.	24.1	79	2.6	wp cor	23500	
		11.8	c′	W.	23.1	82	{ 3.1	w p cor }	40000	
							{ 3.0	wy cor }		
	Aug. 26	10.7	f	W.	—	74	2.8	wp cor	30000	
		12.7	f		23.1	74	2.9	w|r|g	33000	
		3.5	f	N.W.	23.1	75	3.0	wy cor	36500	
	Aug. 27	9.7	f	S.	22.1	68	3.3	wp cor	45500	
		11.7	f	S.	22.1	71	3.0	w o cor	35500	
		3.8	f	S.	22.1	70	2.5	cor	20000	
		5.8	f	S.	22.1	68	2.5	cor	20000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1904	Aug. 28	10.0	f	W.	22.1	74	2.2	cor	13500	
		12.3	f	W.	22.1	78	1.8	cor	7000	
		5.3	f	S.	23.1	73	1.9	cor	8500	
	Aug. 29	10.5	f	W.	23.1	75	3.2	g|b|p	42000	
		11.7	f	W.	—	81	2.8	cor	28000	
		3.0	c	N.W.	23.1	81	2.3	cor	15500	
		5.8	f	N.W.	23.1	76	2.3	cor	15500	
	Aug. 30	9.2	f	E.	22.1	66	2.8	cor	28000	
		12.2	f	E.	22.1	72	2.4	cor	17500	
		5.5	f	E.	22.1	68	2.4	cor	17500	
	Aug. 31	10.3	f	W.	22.1	72	3.7	w r g	61500	
		10.5	f		—	—	4.0	w ro g′	75000	
		12.5	f	W.	22.1	74	3.1	cor	38000	
		3.5	f	S. W.	22.1	73	3.1	g|b|p	38000	
		5.7	f		—	70	2.8	w r g	28000	
	Sept. 1	10.6	f′ H		21.1	70	3.1	w|b|p	40000	
		12.6	f		21.1	70	2.7	wp cor	25000	
		5.0	c′	S.	21.1	68	2.4	cor	17500	
	Sept. 2	9.8	c	S. W.	22.1	74	2.8	w r g	28000	
		12.2	c	W.	22.1	78	3.1	w|b|p	38000	
		3.5	c′	S.	—	79	2.7	wp cor	25000	
		6.0	f H	S.	22.1	74	2.6	cor	22000	
	Sept. 3	10.3	f	S.	23.1	79	3.2	w|b|p	42000	
		12.5	f	S.	23.1	79	3.0	cor	35000	
		3.4	f	S.	—	77	2.8	w|r|g	28000	
		5.4	f	S.	24.1	75	2.3	—	15500	
	Sept. 4	10.4	c R′	N.	24.1	74	2.3	cor	16500	
		12.5	f	W.	24.1	82	3.0	cor	35000	
		6.0	f	N.W.	24.1	74	2.1	cor	11500	
	Sept. 5	10.1	f′	N.W.	23.1	72	3.1	w|b|p	38000	
		12.1	f′	N.W.	—	74	3.1	Do.	38000	
		6.6	f	W.	23.1	70	2.2	cor	13500	
	Sept. 6	9.5	f	N. E.	21.1	62	3.1	g|b|p	38000	
		12.5	f	N. E.	21.1	67	3.0	Do.	36500	
		4.0	f	S. W.	22.1	68	2.8	wrg	28000	
		5.8	f	S.	22.1	63	3.0	g|b|p	36500	
	Sept. 7	10.2	f	W.	21.1	69	3.1	cor	38000	Fog at night.
		12.3	f′	W.	21.1	70	3.1	cor	38000	
		3.7	f	S.	—	68	2.4	cor	17500	
		6.1	f	N.W.	21.1	64	2.8	w r g	28000	
	Sept. 8	10.6	f	W.	22.1	75	3.1	w|b|p	38000	
		12.4	f	W.	—	78	2.8	w r|g	28000	
		5.0	f	S. W.	22.1	77	3.1	g|b|p	38000	
	Sept. 9	10.6	c	N. E.	21.1	60	1.6	cor	5000	
		1.0	c R	N. E.	—	60	1.8	cor	7000	
		5.0	c	N. E.	—	60	2.1	cor	11600	
	Sept. 10	11.8	c	N.	21.1	64	1.9	cor	8500	
		12.1	c	N.	21.1	65	2.3	w r|g	15500	
		6.0	f	N.	22.1	65	2.7	wp cor	26500	
	Sept. 11	10.0	f Fog	N.	21.1	69	2.3	cor	15500	
		12.2	c	N.	21.1	75	3.5	wp cor	55000	Repeated same.
		5.0	c′	S.	22.1	74	1.8	cor	7000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus	Temperature Atmosphere.	Aperture s.	Corona Colors.	Number n.	Remarks.
1904	Sept. 12	10.2	f	W.	22.1	75	2.9	wo	31400	Rain at night.
		12.7	f	S. W.	22.1	81	2.5	cor	21000	
		4.2	f	S. W.	22.1	81	2.2	cor	14500	
	Sept. 13	12.0	f′	E.	21.1	69	2.0	cor	10000	
	Sept. 27	9.8	f	N.	21.1	66	2.9	wg cor	31400	
		3.3	c	N. E.	21.1	69	2.2	cor	13500	Repeated $s=2.2$.
		5.7	c		—	62	2.2	cor	13500	
	Sept. 28	9.4	c	N. E.	20.1	62	2.0	cor	10000	
		3.7	f	N. E.	20.1	67	2.9	cor	33000	
		6.1	f		20.1	60	3.0	g|b|p	35000	
	Sept. 29	9.8	f	S. W.	19.1	66	2.9	cor	33000	
		1.1	c	S. W.	19.1	65	3.0	g b p	35000	
	Sept. 30	10.0	f	S. W.	20.1	72	3.0	w′ b|p	35000	
		11.9	f	W.	21.1	76	3.0	g′|b|p	36500	
		5.2	f R	N.W.	21.1	66	2.6	cor	22000	
	Oct. 1	10.0	f	W.	19.1	60	3.2	wp cor	42000	
		12.4	f		—	62	2.8	w o g	28000	
		5.8	f	W.	19.1	55	2.8	w o g	30000	
	Oct. 2	10.6	c	W.	18.1	58	2.4	cor	17500	
		12.3	c	W.	18.1	60	3.5	wp cor	53000	
		6.5	c′		19.1	57	2.9	w|r|g	33000	
	Oct. 3	9.2	f	N.W.	18.1	54	3.4	wp cor	49000	
		5.0	f		18.1	56	2.5	cor	20000	
	Oct. 4	10.8	f	N.	17.1	58	3.5	wp cor	53000	
		12.3	f	N.	18.1	59	3.0	Do.	53000	
	Oct. 5	9.7	f	W.	17.1	61	3.5	wp cor	53000	
		12.3	f	S.	17.1	63	3.0	w|r|g	35000	
		6.0	f		19.1	58	3.0	Do.	35000	
	Oct. 6	9.6	R	N.W.	19.1	55	2.8	w r g	30000	
		1.3	c′		19.1	59	3.0	g|b|p	36000	
		4.5	f	N.	19.1	—	3.0	w o cor	35000	
	Oct. 7	10.8	f	N. E.	17.1	47	3.9	w o g	70000	
		5.0	f	N. E.	18.1	49	3.0	g|b|p	36000	
	Oct. 8	9.9	c′	N. E.	17.1	55	3.5	wp cor	53000	
		12.6	c	S. W.	17.1	58	3.3	w|b|r	45500	
		5.7	c		18.1	56	3.3	w|b|p	45500	
	Oct. 9	9.6	c		19.1	63	2.4	cor	17500	
		1.0	c	S.	20.1	65	2.3	cor	15500	
		6.6	c		20.1	56	2.2	cor	13500	
	Oct. 10	9.4	c	S.	19.1	57	2.3	cor	15500	
		12.3	c	S.	—	60	2.3	cor	16500	
		5.0	f	S.	20.1	64	3.1	cor	38000	
	Oct. 11	10.1	R	S.	21.1	68	3.4	wp cor	51000	
		1.5	c	N.W.	—	72	2.3	cor	15500	
		4.3	c	N. E.	21.1	61	1.9	cor	8500	
		6.0	c		21.1	57	2.1	cor	11500	
	Oct. 12	9.8	R′	N. E.	20.1	50	2.3	cor	15500	
		12.4	c	N. E.	20.1	50	2.2	cor	14500	
		6.1	c R		20.1	44	2.2	cor	14500	
	Oct. 13	9.6	c	N.	18.1	44	3.8	w r g	66000	
		11.8	c	N.	18.1	46	3.2	w|b|p	42000	
		3.9	c	N.	19.1	48	2.9	w o g	33000	

TABLE 1—*Continued.*

Year.	Date.	Time.	Weather.	Wind.	Temperature Apparatus.	Temperature Atmosphere.	Aperture *s*.	Corona Colors.	Number *n*.	Remarks.
1904	Oct. 14	9.5	f	N.	—	50	3.6	w r g	57000	
		12.4	f		21.1	58	4.1	w o bg	81000	
		4.0	f		20.1	57	2.6	cor	22000	
		6.0	f		20.1	52	3.1	w r g	40000	
	Oct. 15	9.5	f	N.	19.1	49	3.7	wp cor	61500	
		12.3	f	N.	19.1	54	3.1	g′|b|p	40000	
		6.5	f		20.1	50	3.0	g b p	35000	
	Oct. 16	10.0	f	N.W.	18.1	55	4.1	w o bg	83000	
		12.5	f	N.	19.1	62	3.9	w r g	71000	
		5.5	f		19.1	56	3.4	wp cor	51000	
	Oct. 17	9.5	f	S. W.	18.1	56	3.9	w r g	71000	
		12.2	f	S.	18.1	65	3.7	w c g	64000	
		5.0	f	N.W.	19.1	61	3.2	wp cor	42000	
	Oct. 18	9.7	f	S.	—	60	3.8	w c|g	66000	
		12.0	f	W.	18.1	74	2.9	—	31000	
	Oct. 19	9.5	c	N.	19.1	57	2.0	cor	10000	
		6.2	c		19.1	57	2.0	cor	11000	
	Oct. 20	9.6	c	N. E.	19.1	60	2.5	cor	20000	
		1.0	c	S. E.	19.1	63	3.0	cor	35000	
		4.1	c	S.	20.1	63	2.8	cor	28000	
	Oct. 21	9.3	c	S.	20.1	67	2.2	cor	14500	
		4.0	R	S.	—	64	2.9	w r|g	31000	Gale.
		6.3	f		21.1	60	3.1	w br b|p	38000	
	Oct. 22	9.8	f	S.	22.1	59	2.5	cor	20000	
		12.5	f	S.	21.1	62	2.3	cor	16500	
		6.0	f		—	58	3.0	wrg	35000	
	Oct. 23	9.8	f	W.	20.1	53	3.5	wp cor	53000	
		1.1	f	S. W.	20.1	58	3.5	wpcor	53000	
		5.9	f		20.1	53	2.9	w rg	31400	
	Oct. 24	9.3	f	W.	19.1	47	3.3	w	47000	
		4.4	f	N.W.	18.1	51	3.1	cor	38000	
	Oct. 25	10.0	f	W.	18.1	56	3.1	g′|b|p	38000	
		1.0	f	S. W.	18.1	61	{ 3.5 3.1	w r g } gbp }	55000	
		5.5	f		19.1	56	3.4	wp cor	49000	
	Oct. 26	9.4	c	S. W.	18.1	57	3.4	wpcor	49000	
		12.4	R	S. W.	18.1	58	3.1	w b p	38000	
		6.0	c		19.1	54	2.7	cor	25000	
	Oct. 27	9.0	f	N.W.	17.1	44	3.1	w|b|p	40000	
		1.7	c	N.W.	17.1	48	3.2	wp cor	44000	
		5.0	c′	N.	—	53	3.1	g|b|p	38000	
	Oct. 28	9.6	f	N. E.	16.1	39	3.1	g|b|p	38000	
		12.4	f	N.W.	16.1	45	3.6	w c g	57000	
		5.8	f		17.1	43	3.7	w c g	61500	
	Oct. 29	10.2	f	S.	17.1	52	3.0	w|b|p	36000	
		1.0	f	W.	18.1	57	3.7	w c g	61500	
		6.4	f		18.1	50	3.6	w c g	57000	
	Oct. 30	9.9	f	N.	17.1	44	3.9	w r g	70500	
		12.0	f	N.	17.1	46	3.4	wp cor	49000	
		5.4	f		18.1	41	3.0	—	35000	
	Oct. 31	9.3	f	N.	14.1	35	4.3	g b p	90500	
		9.9	f		—	—	4.3	y′ o bg	90500	
		5.0	f	N.W.	16.1	43	4.3	w o bg	90500	

7. *Successive monthly data.*—The temperature effect during the remainder of March (charts 13, 14) is rather in opposition to the above inferences for winter. Thus the maximum on March 19–21 corresponds to a hot wave while the other cases are vague. In other words, there is quite apt to be a rise of nucleation with rise of temperature. The reason for this is frequently to be ascribed to the rain minimum which in winter corresponds to warmer and in spring and summer to colder weather. The Sunday nucleation during clear weather is low on March 15 and high on March 29. The maxima occur for

CHARTS 13, 14, 15.

cloudy (March 17), partially cloudy (March 19–21), and for clear (March 26–29) weather. On March 29–31 the wind and weather change is a complete reversal, and yet the maximum is sustained. Cloud effects appear on March 19, 25, 27, but on the 18th clear weather is ineffective.

8. Throughout the whole of April (charts 14, 15, 16) the nucleation is moderate. The maximum on April 5–7 clearly corresponds to cold weather. The falling off to the minima on April 14–16 is due to the rain-storm, and the subsequent maximum (April 17–19) has no temperature equivalent. The minima on April 26–27 are cloud effects, the air having been purified elsewhere. Remarkably high rain nucleations occur on April 3–5. Night observations on April 18 show no exceptional values. The cusps on April 1, 5, 8, 9, 10, 11, 12, 13 18 are peculiar results.

9. May (charts 16, 17, 18) opens with clear weather but with relatively low nucleation, due probably to the western blizzard. On May 7 and 8 change

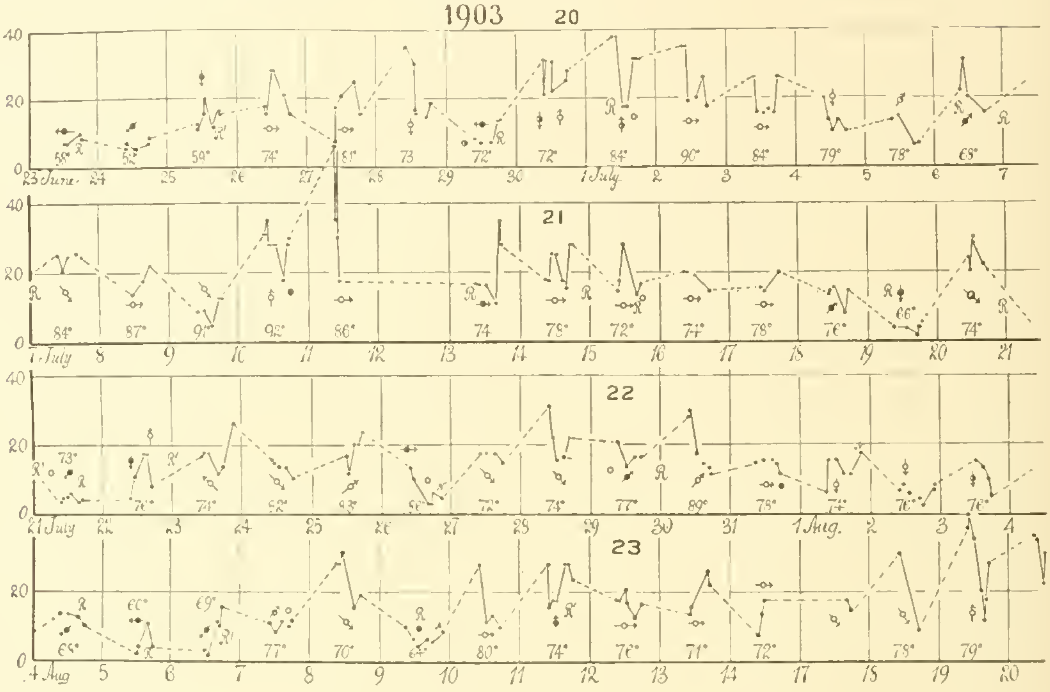
of wind and weather is without effect on the nucleation. On the 20th there is a cloud effect. No specific result marks the hail-storm of May 19. On May 17 and 31 there are low Sunday nucleations for clear weather, but the other Sunday nucleations are high.

CHARTS 16, 17, 18, 19.

10. In the beginning of June (charts 18, 19, 20) hazy weather and relatively high nucleation are due, no doubt, to the New England forest fires, in Maine and elsewhere, which occurred during a period of drought. Intensely yellow fogs, red moons, and greenish suns were observed. The nucleation, however, is by no means remarkably high, not more than twice the normal summer values and scarcely one-fifth of the large winter values—in spite of the excessive fogs. The copious rains which followed the period of droughts gradually reduced the atmospheric nucleation to very small values (June 7–16). The sharp maxima on June 17, 22, 23, are probably due to local fires.

11. In the end of June and beginning of July (charts 20, 21, 22) the nucleation is remarkably high and sustained, changes of wind and weather (June 30, July 1), and even of high temperature (July 3), notwithstanding. Marked rises of temperature and of nucleation concur. Sunday minima with clear weather occur on July 5 only, July 26 being partly cloudy. The effect of gunpowder smoke on July 3 and 4 seems to be quite absent. Rain on July 7, 22, 30 (the latter is even followed by a maximum) scarcely reduces the nucleation, but low values follow the rain-storms on July 18 and 21. The thunder-storms on July 10 and 15 without rain seem actually to be compatible with a rise of nucleation. Incidental night observations on July 23, 26, and August 1 and 2 show no

determinable peculiarity. Throughout the month the temperature effect is vague or in opposition to the winter effect.



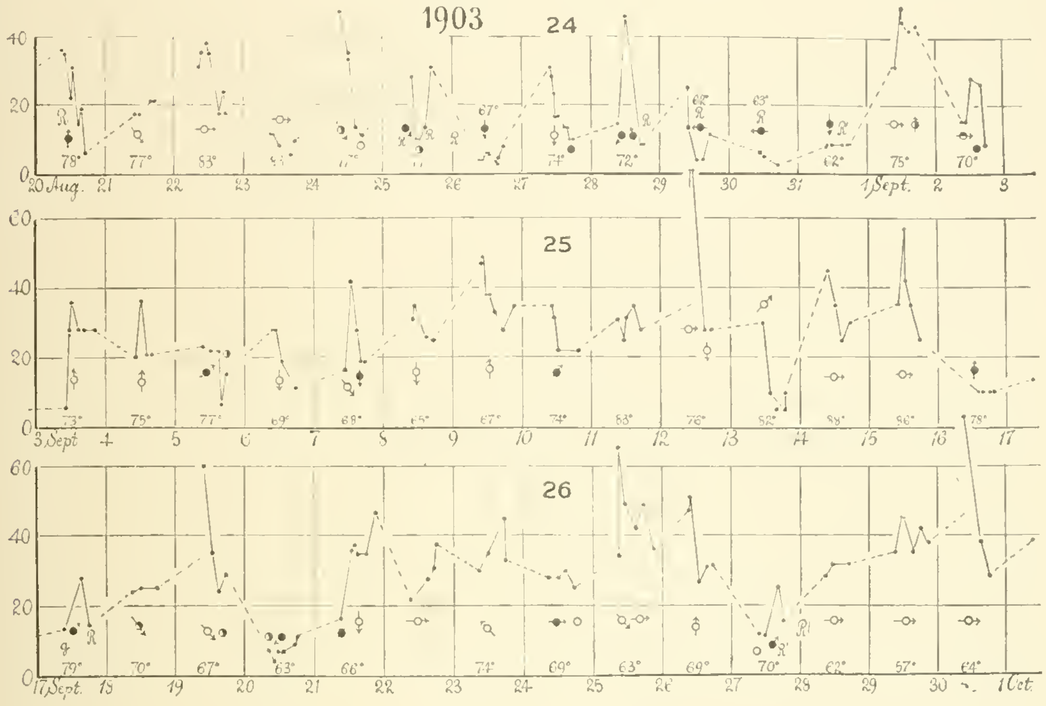
CHARTS 20, 21, 22, 23.

12. August (charts 22, 23, 24) at first shows low nucleation due to frequent rains. The rest of the month is somewhat uncertain in consequence of building operations on the college green. Thus the maxima on the 24th and 25th are due to fires on the campus. Low Sunday nucleations occur on August 2 and 23, the latter being phenomenal. Rapid increase after rain is frequently noticeable, as on August 10, 21, 27, and similar effects may be found in the earlier months.

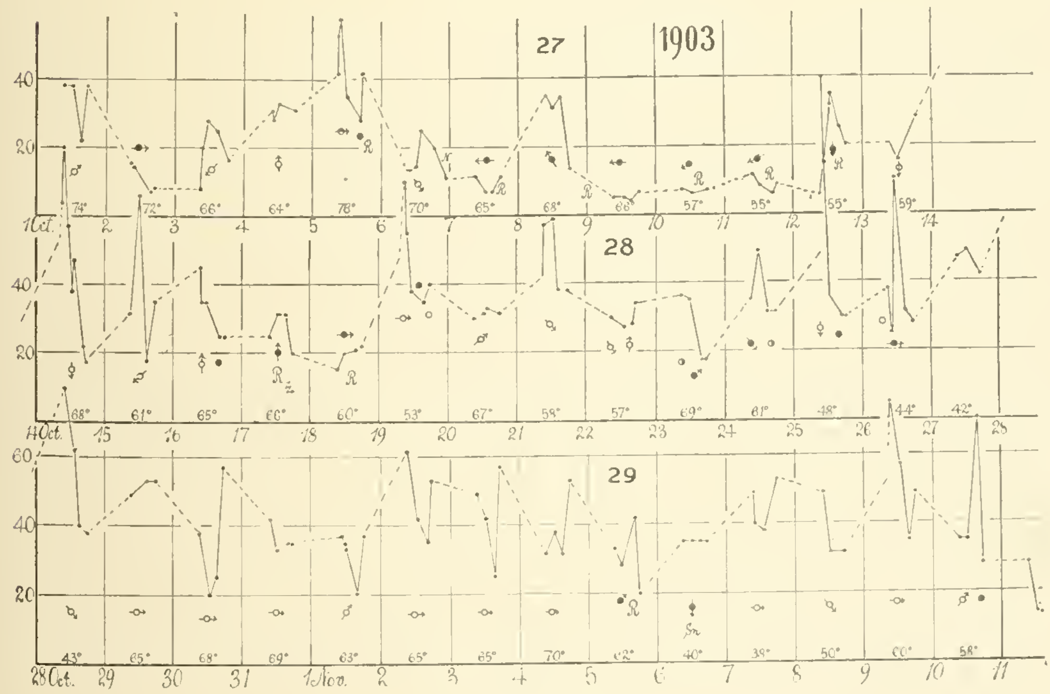
13. September (charts 24, 25, 26), in spite of high temperature, clearly ushers in the high winter nucleations, just as March had removed them. The suddenness in both cases is surprising: one naturally asks whether there is here a return to the locality of the nuclei-producing civil activity which had left it in March. But the data of 1904 do not bear this out. The high maxima on September 1, 9, 12, 15, 19, 22, 25, 30 are all striking. The Sunday minima on the clear days of September 6 and 13 are not low. The gale on September 17 and the thunder-storms on September 5 and 27 are followed by high nucleation, particularly in the latter case, but the assertion that nuclei are produced in this way would be unwarranted.

14. October (charts 27, 28, 29) sustains the high nucleation of September. Sunday minima (October 4, *et seq.*) quite vanish, but the winter temperature effect is not yet resumed. The rain effect on October 5, 12, 17 is obscure, and in the latter case even the rain-storm is ineffective. Rise of nucleation on October 19

is broken by a cloud effect. The occurrence of marked sun-spot disturbances, as announced during the month, may be noted. After October 23 the winter



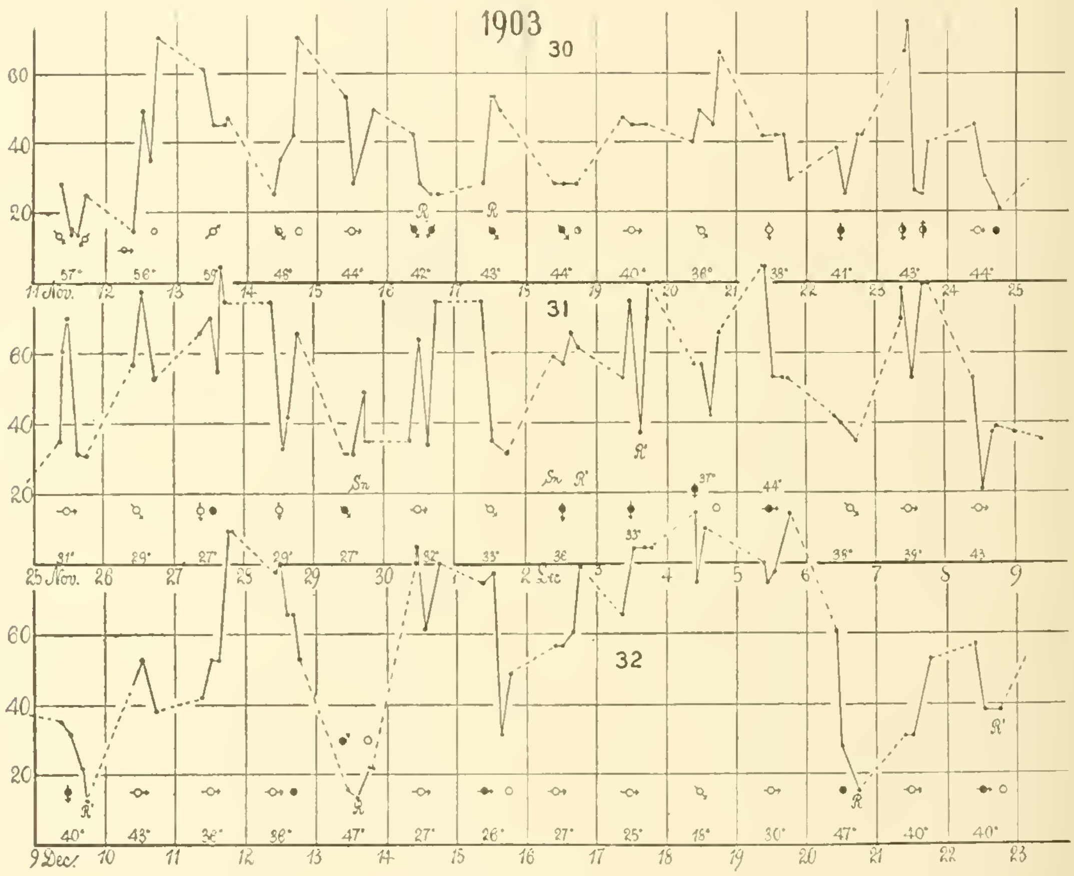
CHARTS 24, 25, 26.



CHARTS 27, 28, 29.

temperature effect is again reinstated, both for the general march through the weeks and for many daily variations.

15. In November (charts 29, 30, 31) the cold wave on the 7th has no counterpart in the nucleation, which is throughout nearly uniformly high. A curious result is the unexplained minimum on the 11th for clear weather, much below the rain effect. After November 22 the sweep toward cold weather on November 27 shows itself in the nucleation. The cold snow on November 29 has but slight, if any, denucleating tendency.

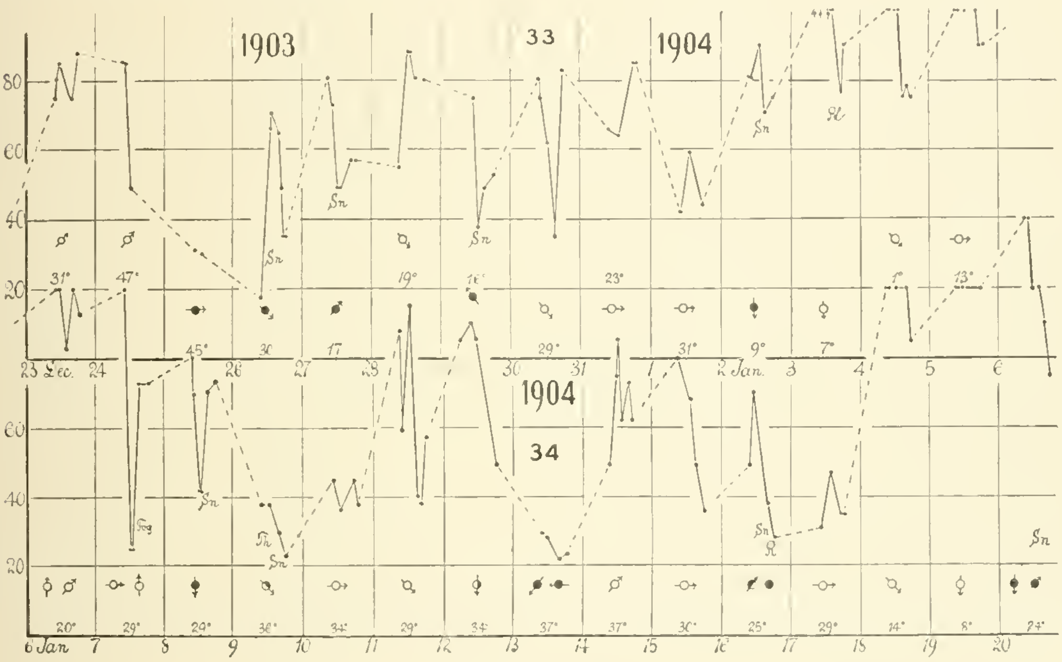


CHARTS 30, 31, 32.

16. So in December (charts 31, 32, 33) the precipitation on the 2d and 3d scarcely reduces the nucleation, and this remains high except during the rains of December 9 and 13. The clear weather minimum on the 8th is noteworthy. From December 10 to the rain-storm of December 21, the temperature effect is very sharply marked, as appears particularly in charted data. The same is true for the remainder of the month. On December 26, 27, 28, precipitation of snow below the freezing-point actually raises the nucleation.

17. *Successive monthly data for 1904.*—With the beginning of the new year, 1904, and very cold weather (charts 33, 34, 35), there is striking parallelism between the temperature curve and the excessively high nucleation, as far as the minimum introduced by the thaw and wet snow on the 9th. The con-

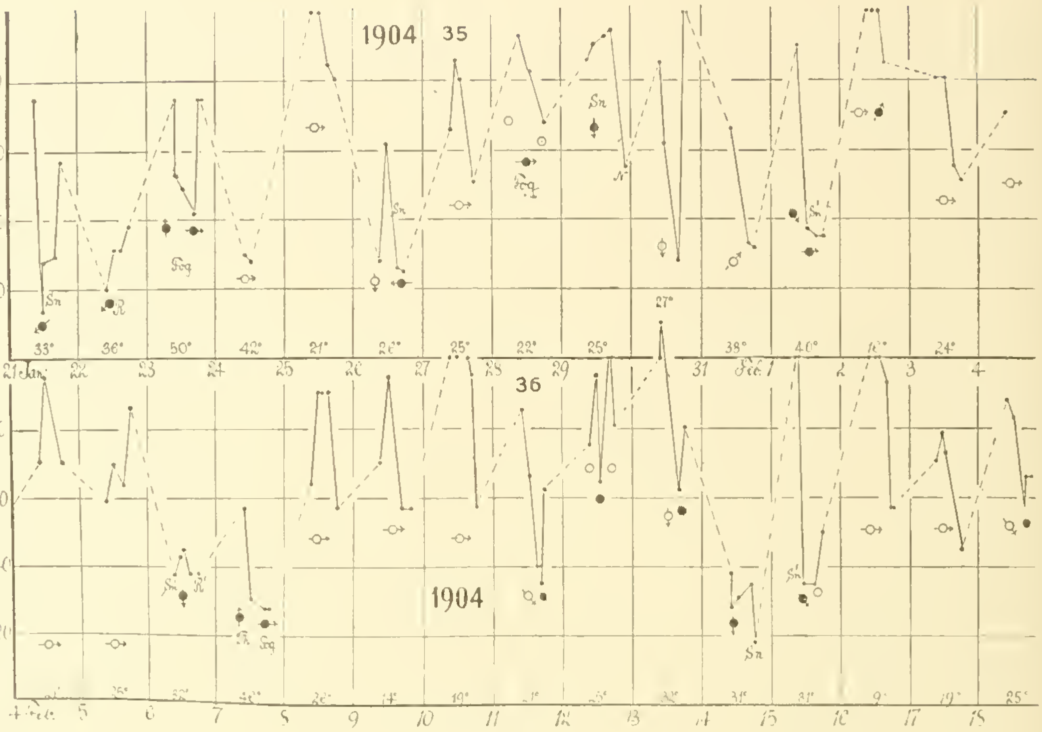
trast between the negligible dry snow effect on January 2 and the wet snow minimum on January 9 is to be noted. The maximum reaches its height (the diffractions actually surpassing the large green-blue-purple corona) during the cold blizzard and snow drift of January 3. As the coronal method breaks down for nucleations exceeding the case for the g-b-p corona, the higher nucleations are merely suggested in value on the charts. There is a fog effect on January 7. Moreover, the maximum is well sustained while the winds shift from northerly to southerly on January 6.



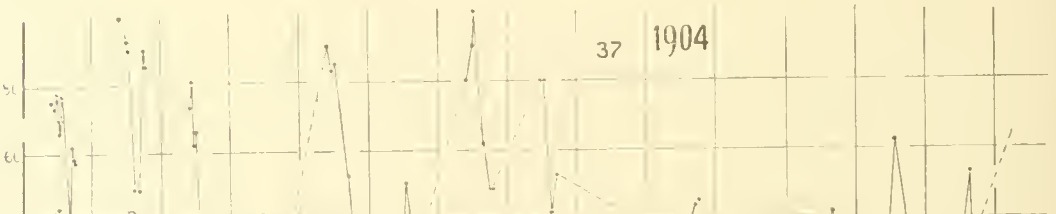
CHARTS 33, 34.

After the rains on January 13 and 16 a second march of nucleation into extremely high maxima (January 18–21) coincides with the sweep of very cold weather, ultimately to be broken by the wet snow on January 21. During the remainder of the month there are some suggestive data on the nucleation accompanying a strong fog, though but few of the active nuclei are probably entrapped in the latter. Cold snow effects on January 26 and 29 may be noticed.

18. February (charts 35, 36, 37) begins with a sweep of cold weather and high nucleation, terminating in the thaw and fog of the 7th. The next cycle extends to the snow on the 14th, a low minimum, remarkable as being below freezing. The temperature effect from February 12–14 is obscure. High nucleation again prevails until the rain and thaw on February 22. The large number of observations entered are due to a number of subsidiary experiments made during this interval. There is cold snow on February 15 and 19. Even the dense snow-storm on February 24 only partially removes the nucleation, as this falls off gradually into the minimum following the rain of February 29.

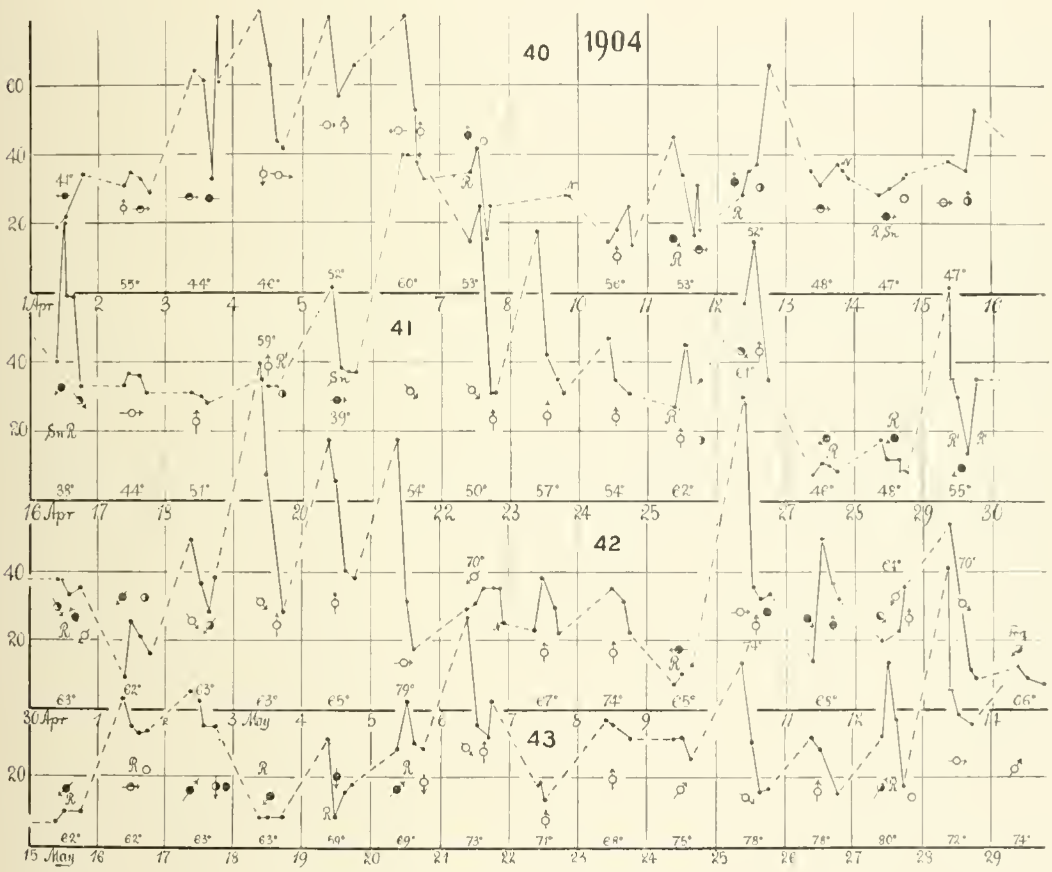


Charts 35, 36.



Charts 37, 38, 39.

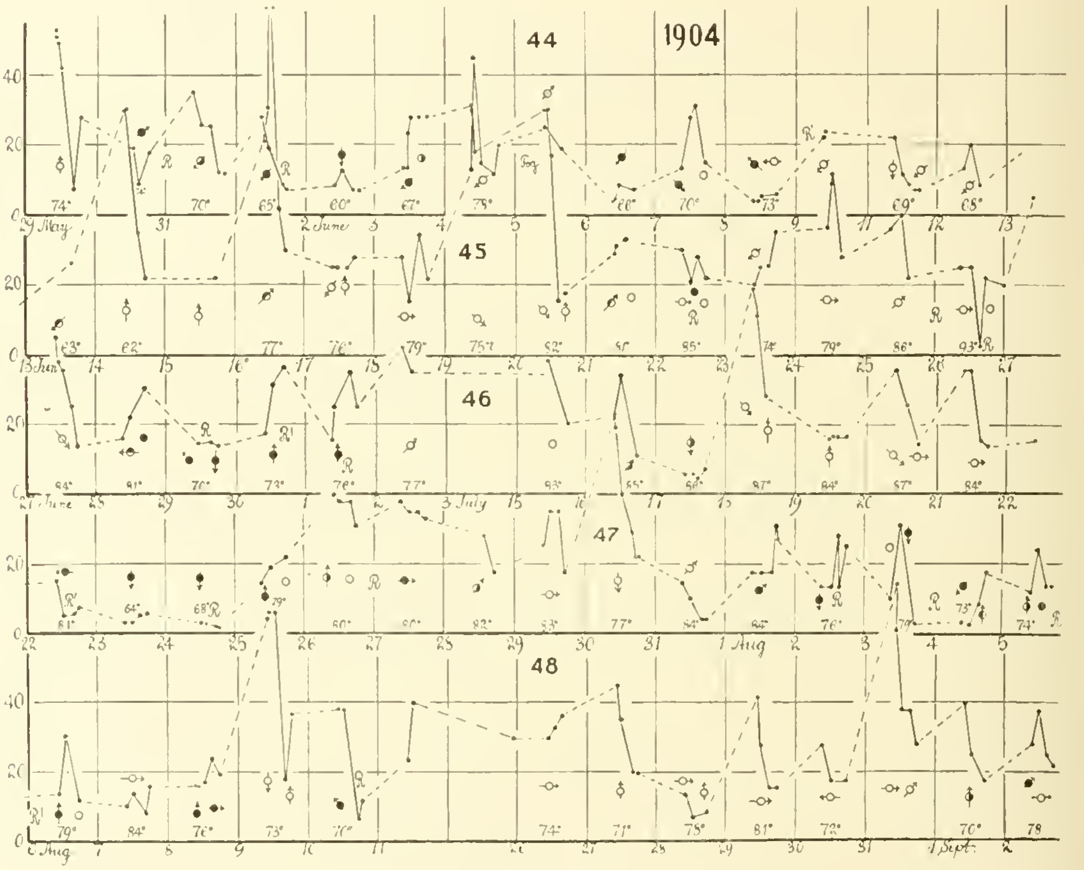
19. The high nucleation of March, 1904 (charts 37, 38, 39), is in distinct contrast to the relatively low nucleation of March, 1903. This is true in like measure for April, May, and even June. In 1904, the winter nucleations are in all cases very gradually replaced by the low summer nucleations. The sweep of temperature from March 1–15 is in very full accord with the changes of nucleation. Remarkably high rain minima occur on March 3, 7, 18, 22, and the same is true of the snow minima on March 11, 15, 18, and of the Sunday minima on March 6, 13, 20, 27. On the 14th there is a cloud effect. Toward the end of the month temperature correspondence ceases and the nucleation remains high, in spite of weather much above freezing.



CHARTS 40, 41, 42, 43.

20. The first period of nucleation, beginning with the rain of April 1 (charts 39, 40, 41) and terminating in the rain of April 7, partakes of the relatively high character for the season already instanced. It is possibly referable to the corresponding sweep of temperature which approaches freezing on April 4, supposing that the nucleation due to fall of temperature outlasts the latter. The period from April 10–18 is less pronounced, but high nucleation corresponds to the moist snows on April 14 and 16. The night observations betray nothing unusual. The final cycle of the month from April 19 to the very low minimum

on April 27 and 28 is again high in nucleation and here there is a reversal of the winter temperature effect, both in the high maximum of April 21 (which comes too late) and the minimum of April 27 (which is also too late). In relation to temperature, both regions have been shifted to the right. The rise of nucleation during the rain of the 29th may be pointed out. There are many results during the month which seem to imply a change of nucleation with the direction of the wind.



CHARTS 44, 45, 46, 47, 48.

21. May (charts 42, 43, 44) also begins with a period of high nucleations, reaching from May 2 to the rain of May 9. The temperature effect is usually reversed or obscure. The contrast with the low nucleation of the preceding year is marked. Rain minima as a whole are low. Strong nucleations (as was the case in April) mark the close of the month.

22. June (charts 44, 45, 46) at last introduces the characteristic summer nucleation, during the first half of the month. The temperature effect is reversed. Sunday nucleations are low on June 5, 12, but not on June 19, which shows phenomenally high values. Abrupt high maxima occur on June 14 and 16. On the 17th there is change of nucleation with the direction of the wind. One may note the sharp reduction of nucleation due to the thunder-storm of June 26. After June 20 the values are as a whole seasonable.

23. Observations during the first half of July (charts 46, 47) were suspended. High rain values occur on July 16, 18, 27, 30. Thus the rain on July 27 has but partially wiped out the maximum. On the other hand, the rain minima on July 23, 24, like those of August 4, are excessively low, being among the lowest nucleations observed (1000–2000 per cub. cm.). Sunday nucleations are not remarkable.

24. The nucleations of August (charts 47, 48) are low at the outset, preceding the abrupt maximum of August 9. The temperature effect is vague. During the middle of the month observations were suspended. The maximum on August 31 suggests the approach of the winter nucleations.

25. September nucleations (chart 48) present no new features and but few are charted. The observations were suspended from September 13 27, during my absence in St. Louis.

GENERAL INFERENCES.

26. *Efficiency of apparatus.*—The experiments as a whole are in the first place to be regarded as a severe test, amounting almost to a strain of the method employed. Since both maxima and minima are registered with equal facility at exceedingly low as well as at high atmospheric temperatures, the temperature error of the method is not menacing. Rain minima, snow minima, and other exceedingly low nucleations have all been recognized. The high maxima require a long apparatus, since the diameters of the corona occupy nearly half a meter at the condensation chamber; but the maximum of atmospheric nucleation does not, except in very rare cases, exhaust the limit of measurable coronas. Nevertheless a higher pressure difference would make it possible to confine the measurements to normal coronas exclusively—a desideratum, inasmuch as Chapters VII. and VIII. have shown that after the g-b-p corona is reached, the data lying in the region of the cusp are estimates. Higher pressure differences are somewhat less convenient, and in regions remote from cities it is improbable that the normal coronas will ever be exceeded. Care must be taken to have the influx pipe far enough from the walls to guard against exhalations from the building in summer. If this pipe is sufficiently long and thin (influx current rapid), the air arrives in the condensation chamber almost at room temperature and without appreciable loss of nuclei during the passage.

27. *Variations of nucleation.*—Mere inspection of the charts shows the extreme variability of atmospheric nucleation, though quiescent periods are also met with. A part of this must be a local effect, even if the changes correspond to the weather. Work in cities where there is so much chance for the pollution of the atmosphere is to some extent unsatisfactory, but the method could hardly have been developed in the country. It is probable that even the small variations of the chart (if they exceed 2000 nuclei per cub. cm.) are real. If the nuclei were colored, the atmosphere would look like mottled soap with

the clear regions usually but by no means always accompanying rain or lying under clouds.

28. *Wind effect.*—Changes of wind velocity were not observed. The nucleation consistently follows certain changes in the directions of the winds, as will appear from a detailed examination of the charts as a whole. The following table, which is a summary of this kind, shows the distribution of maxima above $n = 60000$ with the wind direction.

TABLE II.

WIND DIRECTIONS FOR MAXIMA EXCEEDING $n = 60000$.

Time.	East.	S-East.	South.	S-West.	West.	N-West.	North.	N-East.
Oct., 1902–Jan., 1904....	0	1	0	14	54	25	14	2
Jan., 1904–Sept., 1904...	1	1	11*	10	27	26	11	3

* 8 after March, 2 after May.

By far the greater number of these maxima occur for nearly westerly winds and but few for easterly winds, if stress is laid on the winter nucleations. In 1904, where high maxima occurred in the spring and even in the summer, the distribution is more southerly, but in the main like the preceding. It by no means follows, however, that nucleation is inherently associated with these particular winds, inasmuch as the winds observed are merely those prevailing in Providence. Moreover, the density of population, etc., is far greater towards the southwest than towards the northwest of the University, whereas the northwest winds prevail during the period of maxima.

Considered as a whole, therefore, it is improbable that any real variation of the nucleation with the direction of the winds is in question. What has been observed is the obviously more frequent occurrence of maxima during the prevailing winds.

29. *Rain effect.*—The observation next in importance is the occurrence of pronounced minima during rain, of which the charts contain examples in great abundance. There is rarely an exception to this rule. It implies a faster removal of nuclei by precipitation in a saturated atmosphere (the result of fall of temperature probably) than the supply of nuclei to the same region by either diffusion, or subsidence, or convection, or other more occult causes. Whether this deficiency is eventually made up from the lower air strata in contact with the surface of the earth or from the higher air strata is at the outset left open.

Rain minima never fall quite down to the zero of nucleation, in cities rarely below $n = 1000$, and they are themselves quite variable. Thus the summer minimum is as a rule much lower than the winter minimum.

Minima quite as low as the rain minima are sometimes observed in clear weather, but they are very rare.

One may note that the tendency of rain to change the normal air potential from positive to negative values would thus be accompanied by relative absence of nuclei. In other words minimum nucleation exists here cotemporaneously with maximum negative ionization.

30. *Snow effect.*—Wet snow usually acts similarly to rain, but less powerfully. The effect is particularly noticeable during a thaw. There are cases, however, in which the nucleation is high with a fresh fall of wet snow. Dry snow may even increase the nucleation.

The present experiments, moreover, show that ordinary terrestrial dust, properly so-called, has no bearing on the nucleation; for this is frequently a maximum immediately after a rain, when the earth is blanketed with water, or after the earth has been covered with snow or with sleet to the exclusion of all dissemination of dust as such.

31. *Cloud effect.*—Another interesting feature are the cloud minima as seen on October 15, 17, 21, 23, 1902; March 19, 25, 27, April 1, May 20, August 27, September 27, October 18, 19, 26, December 15, 1903, etc. These observations are incidental, and a larger number would have been found if systematically sought for. Usually a higher nucleation is again established after the cloud train has passed the sky, the phenomenon beginning and ending in periods of clear weather. At other times, however, the minimum remains, as on October 17, when many observations were made with this end in view. The explanation of this result is at hand: the air has moved bodily with the cloud, the whole constituting a region of deficient nucleation. The nuclei may have been precipitated by rain elsewhere and the cloud may even have vanished from the region.

32. *Solar nucleating effect absent.*—Since the nuclei cannot re-enter a region by diffusion as quickly as is usually observed, one may be tempted to infer that solar radiation is the cause by which the nucleation of a deficient region is re-established. There is no evidence of this in the chart and much against it. Thus remarkably low minima are frequently maintained throughout the day in full sunlight. The minimum may be part of a cloud region with which the day closed, but sunlight is powerless to replenish it. Similar references may be made to the notched midday minima which so often occur. By contrast high nucleation develops in spite of an overcast sky. Finally night observations show neither increase nor decrease of nucleation, but are usually normal in character. Hence there is no evidence, so far as these observations go, that ultra-violet light or other solar radiation has any potency in producing the nucleations here immediately in question, and cloud effects have therefore been explained as purely convective. Indeed, compatibly with the final summary (§37) of mean monthly nucleations, the sun must be regarded rather in the light of a denucleating agency.

33. *Temperature effect.*—An important general result is the frequent occurrence of maxima of nucleation, cotemporaneously with the sudden fall of atmospheric temperature in cold weather. So far as the drop of temperature

is concerned, one would have the conditions for the formation and growth of water nuclei, remembering that persistent nuclei may be made in an atmosphere not too far from saturation, from solutions, or in the presence of a solute. Without actual accession to their numbers, however, there could be no increment of nuclei in the condensation chamber at about 20° centigrade. In other words, an actual rise and fall of the number of nuclei per cubic centimeter must occur in the atmosphere at the place of observation.

This temperature or cold-weather effect is very striking in winter where both the daily and the periodic effects frequently coincide. In warm weather the temperature effect is vague or may be even quite reversed. In relation to this one may note that rains in winter usually correspond to rising temperatures, but in summer to falling temperatures. This would accentuate the winter effect, which is otherwise quite independent of rain, but would obscure or even reverse the summer effect, if it exists.

If a polar air current or a current from the upper atmosphere is associated with the cold waves in question, a part of the region where there is continual production of nuclei may be bodily transported to the place of observation.

34. *Local effect.* The prevailing westerly winds sweeping over a part of the city of Providence carry the products of combustion and other local impurities along with them. A large part of the nucleation at the place of observation must therefore be of artificial origin. The local effect should be greater as the wind velocity is smaller and as the temperature is lower. In this way the winter temperature effect is in a manner explained, seeing that fuel will be consumed more rapidly during the cold waves. Observations of wind velocity are inadequate.

The difficulty with this view is that it does not consistently explain all of the observed facts. Thus cold waves occur in winter without maximum nucleation, as, for instance, on November 11, December 8, 1903. The Sunday nucleations during clear weather in summer are not uniformly low. Maxima during relatively warm weather are often quite as high as during very cold weather, the temperature effect is often reversed even in winter, etc. But the most direct reason for caution will be given in the summary of monthly nucleations where it appears that the highest nucleations do not occur in midwinter so far as cold weather is concerned. Speculation as to the origin of the nuclei is thus premature. Whether it is the residue of the ionized products of combustion, or whether ultra-violet light or other radiation at the boundary of the atmosphere is the efficient and preponderating source will only be made clear in a series of correlative observations obtained in a wilderness remote from cities or on isolated mountains. Work of this character is now actively under way.

SUMMARY AND CONCLUSIONS.

35. *Mean daily nucleations.*—Meanwhile it is expedient to deduce from the above data, both the daily and the monthly average nucleations or number

of nuclei per cubic centimeter. Incidental disturbances will thus be to some extent removed at least from the latter, so that the sweep of nucleation throughout the year may be more clearly apparent. The rain effect will be more uniformly distributed during the summer months, though it cannot of course be eliminated.

The data for the mean daily nucleations are given in Table III, and require but little explanation. The symbols for the state of the weather have been abbreviated, f denoting fair, f′ slightly cloudy, c′ partly cloudy, c cloudy, R′ slightly rainy, R rainy, etc. Sn refers to snow, Sn′ to a light snow.

TABLE III.

Mean Daily Nucleations from Oct. 2, 1902, to November 1, 1904.

Year.	Date.	Weather.	Wind.	Nucleation $n \times 10^{-3}$	Year.	Date.	Weather.	Wind.	Nucleation $n \times 10^{-3}$
1902	Oct. 2	c		18	1902	Nov. 7	c		52
	3	f		45		8	f N		37
	4	f		31		9	c		18
	5	c R		12		10	f c		30
	6	R c′		19		11	f		75
	7	f		22		12	c f′		45
	8	f		21		13	c		30
	9	f		16		14	f		45
	10	f		52		15	f		37
	11	c		24		16	f′		7
	12	R c		6		17	c		9
	13	f′		22		18	c		24
	14	R′ f		12		19	c		24
	15	f		24		20	f		42
	16	f c′		18		21	f		90
	17	f c′		13		22	f′		30
	18	c R′		9		23	f′		22
	19	f c′		6		24	c′		34
	20	f		12		25	R c		34
	21	f′		15		26	R		13
	22	f		16		27	c		30
	23	R′ c f		7		28	f′ f		27
	24	f c		21		29	f		75
	25	f′		9		30	f c		36
	26	f′ c		10		Dec. 1	f after R		60
	27	c		31		2	c f		45
	28	R′		18		3	R c		30
	29	f′		21		4	f c		45
	30	f		37		5	c		60
	31	f		30		6	f		100
	Nov. 1	f		22		7	Sn		90
	2	f		24		8	f		75
	3	f		30		9	f		100
	4	f		30		10	Sn c		90
	5	c f		27		11	f′ c		52
	6	c R		45		12	Sn c		37

TABLE III—*Continued.*

Year.	Date.	Weather.	Wind.	Nucleation $n \times 10^{-3}$.	Year.	Date.	Weather.	Wind.	Nucleation $n \times 10^{-3}$.
1902	Dec. 13	Sn c		75	1903	Feb. 2	c R		52
	14	f		100		3	f		45
	15	f c		100		4	R′ c		45
	16	R		36		5	f′		52
	17	f		75		6	f		60
	18	f′		37		7	f		90
	19	f′		90		8	c Sn R		34
	20	f		45		9	f		75
	21	R		33		10	f		45
	22	f′		45		11	f c R		45
	23	f		90		12	f		30
	24	f		90		13	f′		45
	25	Sn c		36		14	f		52
	26	c′		75		15	c Sn′		45
	27	f		100		16 *	Sn		45
	28	f		100		17 *	Sn Bl		60
	29	f c		100		18	f c′		83
	30	f		42		19	f		92
	31	f		100		20	f		93
						21	f		70
1903	Jan. 1	f		100		22	f		30
	2	f		100		23	f		60
	3	R c		40		24	f c		31
	4	f′ c		48		25	f		60
	5	f		55		26	f		62
	6	R Sn f		75		27	f c		39
	7	f c Sn		75		28	R		—
	8	f′ c		45		Mar. 1	c′ f		19
	9	f		100		2	f		61
	10	f		100		3	c		27
	11	c Sn		45		4	f		31
	12	f		75		5	c R′		44
	13	f		100		6	f		48
	14	f		90		7	f		26
	15	c f		90		8	R		20
	16	f′		90		9	R c		13
	17	f		100		10	c		23
	18	f		100		11	R		28
	19	f		90		12	f		32
	20	f c		75		13	f		32
	21	R c′		40		14	f		36
	22	c		45		15	f c		84
	23	f′		42		16	c		22
	24	f		45		17	c		44
	25	Sn		52		18	c f		15
	26	f		45		19	c f		41
	27	c		90		20	f′ f	W.	36
	28	R Fog		45		21	R c	E.	25
	29	c		75		22	R	N.	17
	30	R′ f		75		23	R !	N.E. S.	19
	31	f		60		24	c	S.W.	23
	Feb. 1	c		45		25	f c	W.	19

* End of the approximate data.

TABLE III—*Continued.*

Year.	Date.	Weather.	Wind.	Nucleation $n \times 10^{-3}$.	Year.	Date.	Weather	Wind.	Nucleation $n \times 10^{-3}$.
1903	Mar. 26	f	W.	32	1903	May 17	f	S.	7
	27	f c	W.	37		18	f	W. N. N.W.	14
	28	f	N.	18		19	f c R	N.W. S.E.	12
	29	f	N.	31		20	f R	N.W. S.	21
	30	c	S.E.	39		21	f	N.W. S.	16
	31	R c f	N. W.	26		22	f	W.	15
	Apr. 1	f	W.	27		23	f	N.W.	21
	2	f	S.E. S.	26		24	c f	N.	11
	3	R′ c	S.W.	25		25	f	N.W. N.E.	19
	4	R	S.W. N.W.	26		26	f	S.	18
	5	f	N.W. N.	42		27	c f	S.	22
	6	f	S.	32		28	c′ R c	S.W.	26
	7	R	S.	28		29	f	W. S.	21
	8	R	S. E. S.	21		30	R′ c f	S.	10
	9	f	W.	27		31	f	N.	8
	10	f′	N.W.	24		June 1	f	N.E. S.	16
	11	f	N. W.	25		2	f	N.E. S.	18
	12	f	N.W. W.	24		3	f †	W.	14
	13	f	N.	20		4	Fog †	N.	22
	14	c	E.	13		5	Haze †	N.E. S.	17
	15	R	N.E.	10		6	Haze c	S.W.	20
	16	c	N.E.	13		7	R f	S.	13
	17	c	N.	25		8	c R	S.	13
	18	f	W.	36		9	c	S.	17
	19	f	N.W.	20		10	c	S.	8
	20	f	W.	26		11	R c	E.	7
	21	—	—	—		12	R c	E. S.	5
	22	—	—	—		13	R c f	S.	16
	23	—	—	—		14	f	S.	8
	24	c	W. S.	28		15	R	N.	9
	25	c f	W. S.	24		16	R c	N.	7
	26	c′ c	N.E.	14		17	f	E.	29
	27	f	N. N.E.	13		18	c	E. S.	17
	28	f	N. S.	21		19	c	S.	17
	29	f	N.W. W.	20		20	c	S.	15
	30	f	S.	20		21	R	E.	6
	May 1	c′ f	W. N.W.	17		22	R′ c	N E.	7
	2	f	E.	13		23	c R	E.	8
	3	c	S.	21		24	c R′	N.E.	7
	4	R′ c	N.	23		25	c R′	N.	14
	5	c	N.	18		26	f	W.	20
	6	c c′	N.	14		27	f	W.	18
	7	f c	E. S.	28		28	f	S.	20
	8	f	N.W. S.E.	17		29	c′ R	E. N.E.	9
	9	f	N.E.	8		30	c′ f	N. S.	27
	10	f	S.	20		July 1	R f′	S.	29
	11	f	S.	32		2	f	W.	23
	12	f	S.	30		3	f	W.	19
	13	f	S.	27		4	f	N.	13
	14	f	S.W.	22		5	f′ f	S.W.	10
	15	f	N.W.	15		6	R	S.W.	22
	16	f	N.E.	10		7	f	N.W.	18

† Forest fires.

TABLE III—*Continued.*

Year.	Date.	Weather.	Wind.	Nucleation $n \times 10^{-3}$.	Year.	Date.	Weather.	Wind.	Nucleation $n \times 10^{-3}$.
1903	July 8	f	W.	17	1903	Aug. 31	R c	N.	8
	9	f	N.W.	8		Sept. 1	f'	W. S.	34
	10	f R	S.	27		2	f' c	W. S.	19
	11	f	W.	40		3	f	N.W. S.	25
	12	-	—	—		4	f	S.	24
	13	R c	W.	19		5	c R	W.	18
	14	f	W.	21		6	f	N.	22
	15	R f R' f	W.	18		7	f c	N.	25
	16	f	W.	18		8	f	N.	29
	17	f	W.	17		9	f	S.	39
	18	f' c R	S.W.	13		10	c	S.W.	29
	19	R' c	N.	3		11	f	W.	30
	20	f	N.W.	24		12	f	W.	50
	21	R' f c R c	N.E	44		13	f	S.W.	11
	22	c f	S.	12		14	f	W.	34
	23	R f f'	S.E.	15		15	f	W.	39
	24	f	N.W.	13		16	c	S.	10
	25	f	W.	16		17	c R	S.W.	19
	26	c f	W.	7		18	f'	N.W.	25
	27	f	N.W.	17		19	f f'	N.E.	42
	28	f	N.W.	21		20	c' c	E.	8
	29	c R	S.W.	17		21	f' f	N.	32
	30	f	S.W.	17		22	f	W.	30
	31	f	W.	14		23	f	S.E.	36
	Aug. 1	f	N.	12		24	R c'	W.	28
	2	f	N.	6		25	f	N.W. W.	48
	3	c'	N.	18		26	f	S.	37
	4	c R	N.E.	12		27	f c R c	S.	16
	5	R c	E.	5		28	f	W.	30
	6	c R	N.E.	8		29	f	W.	39
	7	c f	S.W.	10		30	f	W.	53
	8	f f'	N.W.	24		Oct. 1	f	S.W.	34
	9	c R	—	7		2	c	W. N.E.	11
	10	f	W.	16		3	f	N.E.	19
	11	c R	S.	20		4	f	S.	32
	12	f	W.	16		5	f' R	W.	41
	13	f	W.	19		6	f' f	N.W. S.E.	17
	14	f	W.	13		7	c R	E.	9
	17	f	N.	16		8	c c'	S.E.	29
	18	f	N.W. S.	22		9	c' c	E.	5
	19	f	S.	28		10	R	N.E.	7
	20	c R	S.	20		11	R	N.	8
	21	f	N.W.	19		12	R c	N.	23
	22	f	W.	25		13	c	N.	21
	23	f	W.	9		14	f	N.	45
	24	R' f	N.W.	32		15	f	N.E.	40
	25	R c' R	N.W.	21		16	f' c	S.	33
	26	c	N. N.W.	5		17	c R	S.	27
	27	f c	N.	17		18	f' R f	W.	20
	28	c R	N.E. S.E.	22		19	f c f	W.	48
	29	R	E.	12		20	f	S.W.	31
	30	R	E.	5		21	f	N.W.	47

TABLE III—*Continued.*

Year.	Date.	Weather.	Wind.	Nucleation $n \times 10^{-3}$.	Year.	Date.	Weather.	Wind.	Nucleation $n \times 10^{-3}$.
1903	Oct. 22	f	N.W. S.	32	1903	Dec. 13	R f	S.W.	18
	23	f′ c R	S.W. N.W.	26		14	f	W.	77
	24	c c′	N.W.	37		15	c c′ f	W.	58
	25	f c	N.	58		16	f	W.	64
	26	f′	W.	39		17	f	W.	80
	27	f	W.	46		18	f	N.W.	86
	28	f	N.W.	59		19	f	W.	82
	29	f	W.	51		20	R	—	35
	30	f	W.	35		21	f	W.	39
	31	f	W.	36		22	R c f	W.	44
	Nov. 1	f	W. S.W.	32		23	f	S.W.	81
	2	f	W.	48		24	f c	S.W.	73
	3	f	W.	43		25	c	W.	31
	4	f	W.	38		26	c Sn c	N.W.	52
	5	R c	S.W.	31		27	c Sn c	S.W.	63
	6	c Sn	N.	35		28	f	N.W.	76
	7	f	W.	41		29	c Sn	S.E.	54
	8	f	W.	37		30	f	N.W. W.	69
	9	f	W.	59		31	f	W.	72
	10	f c f	S.W.	42					
	11	f	N.W. N.E.	19	1904	Jan. 1	f	W.	48
	12	f′ f	W.	42		2	c Sn	N.	79
	13	f	S.W.	49		3	f	N.	100
	14	c f	N.W. W.	43		4	f	W.	100
	15	f	W.	43		5	f	W. N.W.	100
	16	c R	N.W. N.E.	30		6	f	S. S.W.	97
	17	R	N.W.	43		7	f Fog	W. S.	68
	18	c f	N.W.	28		8	c Sn	N.	67
	19	f	N.W.	46		9	Sn f′ Sn	N.W.	32
	20	f	N.W. N.	50		10	f	W.	41
	21	f	N.	38		11	f	N.W.	63
	22	c	N.	37		12	f c f	N.	75
	23	c R	N. S.	46		13	c R	N.E. E.	26
	24	f c′ c	W.	30		14	f′	S.W.	66
	25	f	W.	43		15	f	W.	58
	26	f	N.	63		16	f′ Sn R	S.W. S.	46
	27	f c	N.	70		17	f	W.	37
	28	f	N. W.	54		18	f	N.W.	100
	29	c Sn	N.	36		19	f	N.W.	100
	30	f	W.	52		20	Sn c	N. S.W.	100
	Dec. 1	f	N.W.	43		21	c Sn	N.E.	41
	2	c Sn R′ c	N.	61		22	R	N.E.	30
	3	c R c	N.	63		23	Fog	S. S.W. W.	59
	4	c f	N.	55		24	f	W.	38
	5	f′ c	W.	66		25	f	W.	91
	6	f	W.	39		26	f c	N. E.	35
	7	f	W.	71		27	f	W.	71
	8	f	W.	42		28	f c c′	W.	81
	9	c R′	N. N.E.	25		29	Sn	N.	91
	10	f	W.	45		30	f	N.	69
	11	f	W.	59		31	f c′	S.	46
	12	f c	W.	69		Feb. 1	c Sn′ c	N.W. W.	48

TABLE III—*Continued.*

Year.	Date.	Weather.	Wind.	Nucleation $n \times 10^{-3}$.	Year.	Date.	Weather.	Wind.	Nucleation $n \times 10^{-3}$.
1904	Feb. 2	f c	W. S. S.W.	96	1904	Mar. 25	c	S.	47
	3	f	W.	67		26	c′	S.W. W.	27
	4	f	W.	78		27	c	E.	29
	5	f	W.	70		28	c	N.W. S.	37
	6	c Sn′ R′	N.	37		29	f	N.W. W.	55
	7	c	S. W.	36		30	f	N.W. S.	43
	8	f	W.	78		31	f c′ R	S.	33
	9	f	N.W. W.	70		Apr. 1	R	E.	26
	10	f	N W.	90		2	f	S. W.	32
	11	f c	N.W.	57		3	c	N.W.	60
	12	f c′ f	N.	86		4	f	N. W.	59
	13	f c	N.	87		5	f	W. S.	68
	14	c Sn	N.	31		6	f	E. S.	57
	15	Sn f	N.W.	56		7	R f	S. W.	29
	16	f	W.	36		8	—	—	—
	17	f	W.	68		9	R	—	28
	18	f c	N.W.	72		10	f	S.	20
	19	c Sn	S.W. W.	66		11	R f′	N.W. S.W. W.	31
	20	f	N.W.	82		12	R c′	S.	41
	21	f	N.	49		13	f′	W.	34
	22	R f	S.W.	30		14	c R Sn f	W.	31
	23	f	S.W.	72		15	f′ c	W. S.	42
	24	Sn! c	N.E. N.	36		16	Sn R f′	N.E. N.	54
	25	f	W.	76		17	f	N.W. W.	34
	26	f	N.W.	64		18	f f′	S.	30
	27	—	—			19	f R′ c′	S. S.W.	34
	28	f c R	S.	38		20	Sn c	W.	43
	29	c	N.E.	25		21	f	N.W.	100
	Mar. 1	c Sn c	E.	29		22	f	N.W. S.	55
	2	f	N.E. S.	38		23	f	S.	46
	3	R	S.	37		24	f	S.	38
	4	f	N.W.	90		25	f′	S.	35
	5	f	N. S.	44		26	f′ f	N.W. S.	56
	6	c c′	S.E. S.	38		27	R	N.E.	9
	7	c R′	S.	38		28	R	N.E.	12
	8	f′ f	W.	31		29	R′	N.E.	35
	9	f	W.	58		30	c′ R c′	N.W. S.W.	35
	10	f	W.	72		May 1	c c′	N. E.	18
	11	c Sn	N.W.	26		2	f	N.W. N.E. E.	38
	12	f	N.W.	61		3	f	N.W. S.	65
	13	f	N.	44		4	f	S.	55
	14	f c′	N.W.	73		5	f	W.	42
	15	Sn c	N.	32		6	f	N.E. S.	33
	16	f	N.W.	49		7	f	S.W. S.	28
	17	f	N.W.	66		8	f	S.	26
	18	Sn R!	S.E. N.W.	36		9	R	E.	10
	19	f	W	44		10	f f′	W. S.	56
	20	f	W.	27		11	c	N.W. S.	32
	21	f	N.	84		12	f	N.W. N.E. S.	25
	22	R	S.	33		13	f	N.W.	24
	23	c f	N.W.	50		14	c	N.E.	9
	24	f	N.W. S.	69		15	c R	N.	9

TABLE III—*Continued.*

Year.	Date.	Weather.	Wind.	Nucleation $n \times 10^{-3}$.	Year.	Date.	Weather.	Wind.	Nucleation $n \times 10^{-3}$.
1904	May 16	f′ R′ f	W.	36	1904	July 19	f	S.	16
	17	c	S.W. S.	39		20	f	N.W. W.	25
	18	c R′ c	N.E.	8		21	f	W.	25
	19	c R	N.	21		22	f′ R	E.	8
	20	c R f	S.W. W. S.	32		23	R c	N.E. N.	4
	21	f	N.W. S.	44		24	c R	N.	2.5
	22	f	S.	16		25	c f	S.	19
	23	f	S.	34		26	f′ f	S.	37
	24	f	S.W.	29		27	R′ f	W.	37
	25	f	N.W.	29		28	f c	S.	23
	26	f′	S.	25		29	c f	W.	28
	27	f′ R f′	S.W.	35		30	f	N.	42
	28	f	W.	49		31	f′ f	S.W.	8
	29	f	S.	38		Aug. 1	c	S.W.	22
	30	c	S.W.	16		2	R	N.	15
	31	f′	N.E.	22		3	f c	N.	15
	June 1	c R	N.E.	16		4	c f	N. S.	8
	2	c	N.	9		5	f′ c	S.	14
	3	c c′	N.E.	22		6	(R) c f	S.	18
	4	f	N.E. S.W.	19		7	f	W.	12
	5	f	S.	22		8	R c	S.E. S. W.	18
	6	c (R)	N.E.	6		9	f	N. S.	46
	7	c R f (R)	N. S.W.	22		10	c R′ c	S.E. E.	23
	8	c f	S.E. E.	5		11	(R) c c′	W.	?32
	9	R′ f′	N.E.	25		26	f	W. N.W.	33
	10	—	—	—		27	f	S.	30
	11	f	N. N.E.	12		28	f	W. S.	10
	12	f	N.	14		29	f′	W. N.W.	25
	13	f′	N.E.	23		30	f	E.	21
	14	f	S.	49		31	f	W. S.W.	43
	15	f	S.	22		Sept. 1	f′	S.	27
	16	f′ R	S.W.	61		2	c f	S.W. W. S.	28
	17	f	N.E.	26		3	f	S.	30
	18	f	W.	25		4	c R′ f	N. W.	21
	19	f	N.	65		5	f′ f	N.W. W.	30
	20	f	S.	46		6	f	N.E. S.W. S.	35
	21	f′ f	S.W.	31		7	f	W. S.	31
	22	f R f	W.	28		8	f. . . R	W. S.W.	35
	23	f	N.E.	27		9	c R	N.E.	8
	24	f	W.	38		10	c f	N.	17
	25	f (R)	S.W.	27		11	f′. . . R	N. S.	26
	26	f R f	W.	25		12	f	W. S.W.	22
	27	f	N.W.	32		13	f′	E.	10
	28	c′ c	E.	23		—	—	—	—
	29	R c	S.E. N.	15		27	f c	N.E.	19
	30	c R	S.	29		28	c f	N.E.	26
	July 1	R c	S. S.W.	25		29	f c. . . R	S.W.	34
	2	f	S.W.	38		30	f R f	S.W. W. N.W.	31
	15	f		29		Oct. 1	f	W.	33
	16	c f	S.	23		2	c c′	W.	34
	17	f′	N.	5		3	f	N.W.	35
	18	f	N.	46		4	f	N.	53

TABLE III—*Continued.*

Year.	Date.	Weather.	Wind.	Nucleation $n \times 10^{-3}$.	Year.	Date.	Weather	Wind.	Nucleation $n \times 10^{-3}$.
1904	Oct. 5	f	W. S.	41	1904	Oct. 19	c	N.	10
	6	R f	N.W. N.	34		20	c	S.	28
	7	c	N.E.	53		21	c R′ f	S. (gale)	28
	8	c	S.W.	38		22	f	S.	24
	9	c	S.	15		23	f	W. S.W.	46
	10	c f	S.	23		24	f	W. N.W.	42
	11	R c	S. N.W. N.E.	22		25	f	W. S.W.	47
	12	R′ c R	N.E.	15		26	c R c	S.	37
	13	c	N.	47		27	f c c′	N.W.	41
	14	f	N.	50		28	f	N.E. N.W.	52
	15	f	N.	45		29	f	S. W.	52
	16	f	N.	68		30	f	N.	52
	17	f	Variable	59		31	f	N. N W.	91
	18	f	S.W.	48					

These data have been constructed in the charts 49 and 50, with the two years of observation overlying the same abscissas to bring out the contrasts. The series for October, 1902–October, 1903, are easily distinguished from the later series, October, 1903–October, 1904, by the continuous curves. The nucleations are given in thousands ($n^{-1/3}$). Clear, partly cloudy, and cloudy weather are indicated on the curves by the usual Weather Bureau symbols—⊙, ◑, ●. Rain is shown by r.

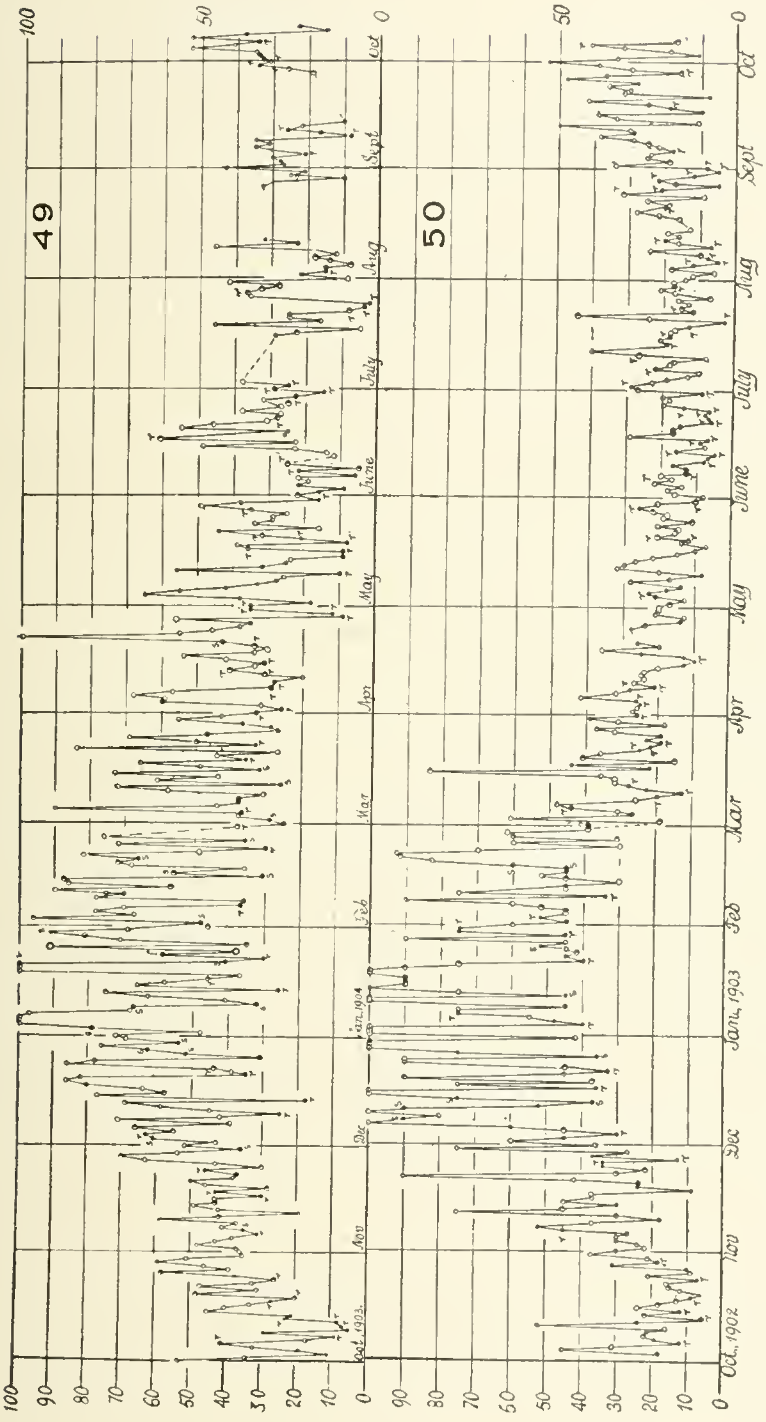
Apart from details, the striking difference of time changes of nucleation, 1902–03 and 1903–04, are apparent. In both cases the high winter nucleations as compared with the summer nucleations are the essential feature; but in 1903 these nucleations fall off almost suddenly and permanently in March, whereas the change in 1904 beyond March is much more gradual.

36. *Mean monthly nucleations.*—The character of these secular changes will, however, appear much more clearly in the monthly averages given in Table IV.

TABLE IV.

Mean Monthly Nucleations from October, 1902, to October, 1904.

Year.	Month.	$n \times 10^{-3}$.	Year.	Month.	$n \times 10^{-3}$.	Year.	Month.	$n \times 10^{-3}$.
1902	Oct.	19.9	1903	Jan.	71.2	1904	Jan.	66.3
	Nov.	35.8		Feb.	55.0		Feb.	60.8
	Dec.	69.4		Mar.	31.2		Mar.	46.5
				April	23.3		April	41.5
				May	17.9		May	30.4
				June	14.1		June	26.3
				July	18.4		July	23.2
				Aug.	15.4		Aug.	22.6
				Sept.	29.4		Sept.	25.3
				Oct.	30.8		Oct.	40.8
				Nov.	42.3			
				Dec.	57.8			



Charts 49–50.—Mean Daily Nucleations (Ordinates) in Thousands per Cub. Centim., Reduced from the Above Charts. In Addition to the Weather Bureau Signs, r Denotes Rain, F Fog.

These data have been plotted in chart 51, the nucleations (n per cubic centimeter) being again laid off in thousands. Both the similarity and the divergences of the results of 1902–03 and 1903–04 become apparent at a glance. It has been possible to connect the successive mean data with a curve almost at once without resorting to much smoothing, except in the summer observations of 1903, where the dotted line is drawn to eliminate the probable and excessive rain effect, as well as the effect due to building operations on the college campus, etc. It should be noticed that the new data for 1904 (August, September, October) fall very closely upon the curve for 1903 prolonged. As stated above, § 3, the results from October, 1902, to March, 1903, are reduced from the old scale and are not at once comparable in absolute magnitude with the remaining data, but the relations are nevertheless well indicated.

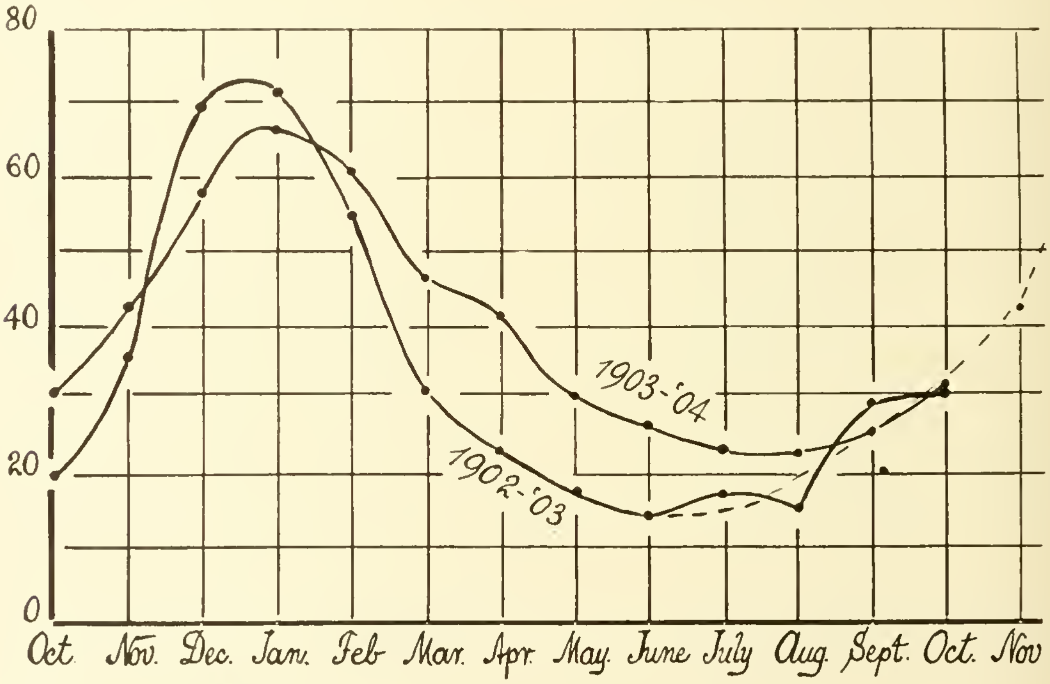


Chart 51.—Mean Monthly Nucleations (Ordinates) from October, 1902, to October, 1904, in Thousands per Cub. Centim.

37. *Occurrence of maxima and minima of nucleation during the winter and the summer solstices, respectively.*—The remarkable result of both curves is unmistakable: remembering that the mean nucleations hold for the middle of the month, the maxima of nucleation both in 1902 and 1903 occurred between the middle of December and the middle of January, nearer the latter; in other words, about at the time of the winter solstice. The minima for summer occur between the middle of June and the middle of August somewhat after the summer solstice. The winter maximum is in both cases sharply indicated and

its coincidence with December 22 not improbable. The summer minimum is much more prolonged and uncertain, a result to be anticipated from the marked rain effect which prevails at this season.

The identification of maxima with the winter solstice and of minima with the summer solstice is alluring: for in these cases the earth is respectively nearest and farthest from the sun. At the same time the orbital velocities are respectively greatest and least, so that the path volume of the earth would have corresponding values. Both causes are qualitatively in harmony with the observed results, if the nucleation comes in great part from the sun. Quantitatively the results are less convincing.

If the data for 1903–04 (which are more nearly absolute) be taken, the ratio of greatest and least nucleation is about 3, seeing that December 22 corresponds to about $n=66000$ and June 22 to $n=22000$. The case of 1902–03 is even more accentuated. On the other hand, the greatest and least values of the radius vector of the earth's orbit are 1.0168 and .9832, in terms of the mean radius. The same effect, approximately, is attributable to the differences in velocity, making only about 6.7 % by which the winter nucleation should exceed the summer nucleation, for the case of linear distribution. No easily discernible distribution of nuclei from the sun outward would account for the three- to four-fold winter nucleation as compared with the summer nucleation, seeing that the decrement of about 2 % of distance corresponds to an increment of 100 % of nucleation. Thus the reasonable surmise which makes the density of the solar output vary as the inverse square of radius, while the path volume per unit of time varies as the inverse radius, gives a compound law of the inverse cube of radius, which, however, is quite inadequate.

Unless some occult law of distribution is at the root of these cases, mere change of distance and velocity does not account for the facts. On the other hand, if the influence of the sun is atmospheric and productive of dissipation of nuclei (by breaking them into fragments beyond the lower limit of nuclear size, for instance), or if there is greater tendency toward supersaturation of the atmosphere when the nights are longest with the consequent precipitation of local nuclei, the effect due to greater length of days in the summer as compared with the winter will much more nearly correspond to the nucleations observed. The effect postulated is, however, wholly conjectural.

38. *Conclusion.*—On the other hand, the two graphs showing the distribution of mean monthly nucleation are not compatible with the postulate of a purely local or incidental origin of the nuclei. Rains in general would make the winter nucleation higher than the summer nucleation, while the products of combustion still further increase the former. But neither of these incidental effects is so distributed as to give rise to the salient maximum in December, reproduced independently and sharply by both curves.

Briefly, then, while local and incidental effects enormously modify the seasonal variation of atmospheric nucleation, it is not improbable that its origin is in part to be traced to a more deep-seated cause. At least the results obtained are sufficient to warrant the extension of similar experiments over a wide area of territory, including regions remote from the habitations of man—researches for which I am now making extensive preparation.

SMITHSONIAN CONTRIBUTIONS TO KNOWLEDGE

PART OF VOLUME XXXIV

GLACIERS OF THE CANADIAN ROCKIES AND SELKIRKS

(SMITHSONIAN EXPEDITION OF 1904)

BY

WILLIAM HITTELL SHERZER, Ph.D.

(No. 1692)

CITY OF WASHINGTON
PUBLISHED BY THE SMITHSONIAN INSTITUTION
1907

The Knickerbocker Press, New York

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Commission to whom this Memoir has been referred :

THOMAS CHROWDER CHAMBERLIN
HARRY FIELDING REID
GEORGE PERKINS MERRILL

The Knickerbocker Press, New York

ADVERTISEMENT.

Doctor William H. Sherzer, Professor of Natural Science at Michigan State Normal College, has brought together in the present memoir the results of an expedition undertaken by the Smithsonian Institution among the glaciers of the Canadian Rockies and Selkirks in the year 1904. The general objects of the research were to render available a description of some of the most accessible glaciers upon the American continent, to investigate to what extent the known glacial features of other portions of the world are reproduced in these American representatives, and to ascertain what additional light a study of similar features here might shed upon glacier formation and upon some of the unsettled problems of Pleistocene geology.

A systematic survey was made of the Victoria and Wenkchemna glaciers in Alberta and of the Yoho, Asulkan, and Illecillewaet glaciers in British Columbia, located about two hundred miles north of the boundary of the United States. The largest of these is the Yoho Glacier, extending more than three miles below the névé field, and a mile in width for two-thirds of its length. Doctor Sherzer investigated various surface features of each of these glaciers, the nature and cause of ice flow, the temperature of the ice at various depths and its relation to air temperature, the amount of surface melting and the possible transference of material from the surface to the lower portion; their forward movement and the recession and advance of their extremities, and the general structure of glacial ice.

In summarizing the most important results Doctor Sherzer discusses the indicated physiographic changes in the region during the Mesozoic and Pleistocene periods; the question of precipitation of snow and rain, and the effect of climatic cycles on glacial movements, the structure of the ice as to stratification, shearing, blue bands, ice dykes, glacial granules, and the possible methods of their development. In discussing the theories of glacial motion the author expresses his conviction that the nature of the ice movement can be "satisfactorily explained only upon the theory that under certain circumstances and within certain limits ice is capable of behaving as a plastic body, that is, capable of yielding continuously to stress, without rupture," but "the plasticity of ice, a crystalline substance, must be thought of as essentially different from that manifested by such amorphous substances as wax or asphaltum."

Doctor Sherzer also discusses the cause of the richness and variety of coloring of glaciers and glacial lakes.

In accordance with the rule of the Institution this paper has been referred to a commission consisting of Professor T. C. Chamberlin, of the University of Chicago; Professor Harry F. Reid, of Johns Hopkins University, and Doctor George P. Merrill, of the United States National Museum, and upon their favorable recommendation is published in the series of "Smithsonian Contributions to Knowledge."

Richard Rathbun,
Acting Secretary.

Smithsonian Institution,
Washington, D. C., January, 1907.

PREFACE.

The five glaciers selected for investigation are located in Alberta and British Columbia, along the line of the Canadian Pacific Railway. They represent the great snow-ice masses which accumulate, season after season, upon the higher slopes and within the amphitheaters of the Selkirks and Canadian Rockies, the slow downward movements of which prevent indefinite accumulation and bring these great ice bodies to a level where complete melting may occur and the waters again be put into circulation. The observations here described were begun by the writer in the summer of 1902 and continued through the seasons of 1903, 1904, and 1905; the entire field season of 1904 being devoted to the surveys and more detailed studies.[1] Camps were established in the immediate vicinity of the glaciers selected and they were kept under almost continuous observation during the hours of daylight. Beginning with the nose of each glacier, surveys around either side to the névé field were made with plane-table, transit, or compass; the measurements being with a steel tape. It was found impracticable and unnecessary to traverse the névé areas and those portions mapped were drawn from field observations and original photographs together with maps and illustrations from the Canadian Topographic Survey, and other sources. The writer was ably assisted by Mr. DeForrest Ross and Mr. Frederick Larmour, to whom he desires to make grateful acknowledgment for intelligent and faithful service, rendered often under trying circumstances. During the latter part of the season of 1905 very efficient assistance was rendered by Messrs. E. W. Moseley and O. K. Todd.

Being the most accessible glaciers upon the American continent it was desired to render available as complete a description as time and facilities would permit and to ascertain to what extent the known glacial features of other portions of the world are reproduced in these American representatives. It was hoped that a study of the same features, produced under somewhat different conditions, might shed additional light upon their method of formation and upon some of the unsettled problems of Pleistocene geology. A disproportionate amount of time was devoted to the Victoria Glacier, at the head of the superbly beautiful Lake Louise Valley, since this glacier is geologically the most interesting and may well be taken as a type by students of glaciology. A delightful camp site lies under the lee of the outer massive block moraine and a still more picturesque one farther up, on a low shoulder of Mt. Whyte, over-

[1] A preliminary report upon the expedition appeared in May, 1905, in the "Smithsonian Miscellaneous Collections," vol. 47, Quarterly Issue, pp. 453 to 496.

looking the small lakelets. Students who may carry this report into the field generally desire an explanation which they can put to the test, upon the spot, and so an attempt has been made at interpretation of the various phenomena described. The value of such interpretation will be known only after others have passed judgment upon the same features and more extended observations are available.

Numerous forest fires in the season of 1904 prevented distant photography, on account of the smoke or haze, but through the courtesy of the Dominion Topographic Survey and of the Detroit Publishing Company we are permitted to reproduce some of their general views, obtained under favorable conditions. In addition to the views so used the writer is indebted to Captain Eduard Deville, Surveyor General of Dominion Lands, and his Chief Topographer, Arthur O. Wheeler, for a series of maps and photographs and much information concerning the regions under study. To the Director, R. F. Stupart, of the Canadian Meteorological Service, to the Assistant Director, B. C. Webber, and to Mr. N. B. Sanson, very grateful acknowledgment is made for meteorological data relating to British Columbia and Alberta and for the use of instruments kindly placed at the disposal of the expedition. Very sincere thanks are hereby tendered also to Prof. Joseph B. Davis, of the University of Michigan, and to Prof. Elmer A. Lyman, of the Michigan State Normal College, for the use of surveying instruments. The writer further desires to express his deep gratitude to the officials and employees of the Canadian Pacific Railway, who permitted the use of their Swiss guides for the necessary higher climbing and in many ways rendered very substantial assistance to the expedition. Finally to the packers and outfitters, Messrs. Robert W. Campbell and George W. Taylor, with their indispensable though often unwilling cayeuses, the writer desires to gratefully acknowledge the most generous and courteous treatment.

W. H. Sherzer.

The Michigan State Normal College,
Ypsilanti, Mich., December, 1906.

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Mt. Lefroy. Mt. Victoria. Mt. Whyte.

Mount Victoria and Lake Louise, Alberta, Canadian Rockies. Reproduced by courtesy of Detroit Photographic Co.

GLACIERS OF THE CANADIAN ROCKIES AND SELKIRKS

(Report of the Smithsonian Expedition of 1904.)

By William Hittell Sherzer, Ph.D.

CHAPTER I.

INTRODUCTION.

1. Geographical Data.

a. Physiographic features.—The Canadian Pacific Railway crosses the Rockies and Selkirks between north latitude 51° and 51° 30′, working its way up the left bank of the Bow River and its small tributary Bath Creek, to the Kicking Horse Pass, attaining an altitude of 5,329 feet above sea-level. Upon the more abrupt western slope of the Rockies the road follows the left bank of the Kicking Horse River to its junction with the Columbia, crosses this great waterway of the mountains, and slowly ascends the eastern slope of the Selkirks along the left bank of the Beaver. The summit of the Selkirks, Rogers' Pass, is crossed at an elevation of 4,351 feet, whence there is rapid descent along the swift-flowing Illecillewaet to the Columbia again, which has encircled the system to the north, forming the "Big Bend." These transverse mountain valleys are lined with most majestic peaks, many of them rising a mile above the valley floor and furnishing some of the grandest of mountain scenery upon the American continent. The highest peak in the Rockies, seen from the railway, is Mt. Temple, with an elevation of 11,627 feet, and in the Selkirks, Mt. Sir Donald, 10,808 feet. Numerous peaks range from 10,000 to 11,000 feet and are believed to culminate to the northward in latitude 52° to 53°.

The Rockies and Selkirks, together with the Gold and Coast ranges to the west, make up the Great Cordillera in this part of Canada. North of the international boundary this great system is much narrower than in the United States, having a total width of about four hundred miles, and the component ranges are straighter and more regular. The systems are progressively higher from the coast eastward, culminating in the Rockies proper, which stand as a lofty buttress along the western margin of the great central plains. Between the Coast and the Gold ranges there lies an interior plateau a hundred miles wide with an average elevation of about 3,500 feet above sea-level. The Gold, Selkirk, and Rocky systems are separated by the Columbia and the Columbia-Kootenay valleys, made by the action of water and ice along the strike of the geological formations, assisted probably by some dislocations of the strata.

The Rocky Mountains, or as formerly called, the Stony Mountains, consist of an imposing array of parallel ranges with a general trend in this region of north-northwest to south-southeast, separated by longitudinal valleys and attaining a total breadth of 40 to 50 miles. Compared with the systems to the west they are strikingly rugged in character and free from vegetation. Skirting the eastern border, and a part of them both geologically and structurally, are the "foot-hills," consisting of folded parallel ridges, reaching out 15 to 20 miles and merging into the "plains" at an elevation of about 3,300 feet.

b. Streams.—The main streams occupy the longitudinal valleys for a portion of their course, leaving the mountains by the transverse valleys, which extend into the foot-hills. According to Dawson the base-level of the streams upon leaving the mountains to the eastward is about 4,360 feet, while to the west it is about 2,450 feet above sea-level. Upon the eastern slope of the Great Continental Divide the waters are gathered into the Saskatchewan and reach the Atlantic Ocean by way of Hudson Bay; while those to the west drain into the Columbia River and work their way to the Pacific Ocean. As pointed out by Dawson, the actual water parting does not correspond entirely with the highest crest line of the mountains, but lies to the eastward, in which direction it seems to be moving. Between the international boundary of north latitude 49° and 52°, the Rocky Mountains are sharply separated from the Selkirks to the west by the Columbia-Kootenay Valley, which maintains a considerable breadth and a remarkably straight course through more than three degrees of latitude. This valley is filled with drift materials to a considerable depth and is undergoing but little erosion, the river simply cutting tortuous channels through the loose deposits. The eastern side of the valley is generally steep and escarpment-like, while the western is rounded and wooded. The Columbia starts within a mile and a half of its southward-flowing tributary, the Kootenay, and moves northwestward in a great sweep as though intent upon capturing the drainage of the region before starting for the sea. In this great fold it encloses and sharply limits the less rugged, but picturesque, Selkirk System, with its subdued outlines and forested slopes. Some of the eastern ranges are continuous and have the same general trend as those of the Rockies, but, in general, there is less regularity and continuity in the arrangement of crests and peaks, and they do not attain as great a height. The drainage is all into the Columbia River, and the streams are unable to develop any considerable size. Being so largely glacier fed here, as well as in the Rockies, the streams maintain themselves during the summer months, but reach their highest stage in the late spring, or early summer, from the melting of the snows, when the Columbia may rise 30 to 40 feet above its usual level. The streams are generally turbid with glacial sediment that gives them a milky, or yellowish, appearance, changing to green and, upon the loss of the sediment, to a blue color wherever the water is of considerable depth. The lakes of the region owe their origin mainly to former glacial action, consisting either of rock-basins, or of depressions in the glacial or fluvio-glacial deposits. Certain ones have been dammed back by morainic material deposited either beneath or at the extremities of glaciers of greater extent than at present. Those lakes which receive glacial sediment, or which are shallow, have a greenish cast, while those free from sediment and of moderate to considerable depth are rich blue.

c. Glaciers selected for study.—The glaciers selected for study lie close to the main crests of the systems above described, between north latitude 51° and 52°, and west longitude 116° and 117° 30′, from 160 to 200 miles north of the international boundary between the United States and Canada. They are but a few of a series available for study, those being selected which are most easily reached by well established trails. They are at such low altitudes that one may comfortably ride almost to the nose of each and none require climbing except to reach the névé regions. The two most easterly of the glaciers here discussed, the Victoria and Wenkchemna, lie east of the Great Divide in Alberta, the other three are west in British Columbia.

2. Historical Data.

The establishment of the international boundary to the south, along the 49th parallel, and the opening of the railway in 1885 called for geographic, geologic, and topographic work which was started by the various Dominion departments concerned and is still in progress. Dr. George M. Dawson began his work in 1874 along the boundary and extended it northward to include the region pierced by the railway, where he was assisted by R. G. McConnell. Topographic work of a preliminary nature, along the line of the railway, was begun in 1886 by J. J. McArthur. Photographic methods were introduced into the survey in 1889 by Director Deville and the accompanying triangulation of the "railway belt" placed in charge of W. S. Drewry, D. L. S. The same year Mr. St. Cyr made a survey along the upper Columbia, between the Selkirks and Rockies, and in 1896 he and McArthur continued the work from Revelstoke down the Columbia and Arrow Lakes, with the view of connecting the surveys of the railway belt with those of the boundary commission.[1] Two topographic maps, upon a scale of two miles to the inch, were issued in 1902 by the Department of the Interior, under the direction of James White, geographer. These are the Banff and Lake Louise sheets and are issued by the department at

[1] The reports of the work of McArthur, Drewry, and St. Cyr will be found in the Annual Reports of the Canadian Dept. of the Interior for 1886, 1888 1889, 1890 1891, 1892, and 1893.

Ottawa. The topographic work of the mountains is now in the hands of Mr. Arthur O. Wheeler and there is being issued an enlarged map (scale 5,000 feet to an inch) of a section of the mountains lying between the railway and the Great Divide and extending from the Kicking Horse to the Vermilion Pass. This map includes completely the regions surrounding the Victoria, Horseshoe, and Wenkchemna glaciers, with corrected elevations, essentially the same territory covered by Wilcox's map, 1896, on the scale of an inch and a half to the mile. Based upon work done during the seasons of 1901 and 1902, there will be issued with vol. II of Wheeler's *Selkirk Range* an admirable piece of mountain mapping, extending from the Columbia to the Columbia, across the Selkirks along the line of the railway.

The opening of the railway and the wonderful attractions of the region brought in a body of non-professional explorers and mountaineers, among the first of whom was the Rev. W. S. Green, Carrigaline, Ireland. He spent the working season of 1888 in the Selkirks, using Glacier House as a base, and gathered material for an interesting volume, *Among the Selkirk Glaciers*, Macmillan & Co., 1890. The map accompanying the volume, originally published in the *Proceedings of the Royal Geographical Society*, vol. XI, 1889, was the first attempt at detailed mapping in the Selkirks. One year earlier than Green, in 1887, Messrs. George and William Vaux, Jr., of Philadelphia, visited Glacier House, secured a valuable collection of photographs and began a series of observations upon the glaciers to which frequent reference will be made in the later chapters of this report. During the closing decade of the last century, and the opening decade of the new, there has been much work done in the region of an exploratory and mountaineering character. There should be mentioned especially the names of Wilcox, Fay, Parker, Collie, Stutfield, Allen, Habel, Topham, Thompson, Huber, Sulzer, Noyes, and the English ladies Benham, Tuzo, and Berens. Besides three superbly illustrated and attractively written volumes by Wilcox, Wheeler, and, conjointly, by Stutfield and Collie,[1] there have been prepared a number of descriptive papers for the scientific societies and magazines. A bibliography of the region, full but not complete, will be found in *Appalachia*, vol. X, 1903, pp. 179 to 186. The Canadian artist, F. M. Bell-Smith, of Toronto, has spent many seasons in the mountains and, based upon the various maps, photographs, and original sketches, has prepared relief maps of the best known areas of the Rockies and Selkirks. Copies of these maps are placed in the hotels operated by the railroad.

It is not likely that these mountain valleys ever supported anything more than a scant Indian population, owing to the scarcity of fish, game, and available pasture. Providing food, en route, has always been a precarious matter for exploring parties. Aside from the marmot and rock-rabbit and an occasional porcupine, there is a strange and impressive feeling of desertion. The few

[1] *Camping in the Canadian Rockies*, Wilcox. G. P. Putnam's Sons, N. Y., 1896. *The Rockies of Canada*, Wilcox. Putnams, 1903. *Climbs and Explorations in the Canadian Rockies*, Stutfield and Collie. Longmans, Green & Co., N. Y., 1903. *The Selkirk Range*, Wheeler. Government Printing Bureau, Ottawa. 1905.

birds that one meets seem awed into silence by the grandeur of their surroundings. The mountain Crees had possession of the region at the coming of the white traders and trappers, but within rather recent time have been assimilated by the Stoneys, a tribe of Assiniboines, from the plains to the east.

3. Geological Data.

a. Stratigraphy. The first work of a geological nature in this region was by Dr. Hector in 1858 to 1860, as a member of the Palliser expedition, his observations being confined mainly to the Rockies and the region to the east. A geological map and numerous sections were prepared to accompany a paper presented to the Geological Society of London, in advance of the publication of the results of the expedition.[1] For detailed knowledge of the geology of the Rockies and Selkirks we are indebted mainly to Dr. George M. Dawson and his assistant R. G. McConnell, the former of whom began his work in 1874, as geologist of the boundary commission. The Bow River region was entered in 1881 and in the Annual Report of the Geological Survey for 1885 there was published a preliminary report upon the geology of the Rockies lying between the boundary and north latitude 51° 30′. The report was accompanied by a large scale geological map, which was followed the next year with a geological section by McConnell, approximately along the line of the 51st parallel of latitude. Work was extended westward into the Selkirks and, at the Washington meeting of the Geological Society of America, Dr. Dawson, in 1890, presented the results of his observations amongst these ranges.[2] The present Geological Survey, under the directorship of Robert Bell, is still at work upon the detailed study of portions of the region.

The Selkirks and Rockies consist of an enormous complex of sedimentary strata, 50,000 to 60,000 feet in thickness, underlain by crystalline rock. In age they range from the Archæan to the Laramie, at the close of which the final stages of upheaval were accomplished. The rock strata graduate in age from the west, eastward, and were folded and faulted by pressure from the west, by which they were forced against the resistant layers underlying the "great plains." The crystalline rocks of the series, of presumable Archæan age, consist of gray gneisses, passing into schists, and occur only along the western margin of the Selkirks, where they constitute the Shuswap series. No trace of them has yet been discovered in the Rockies. Overlying the series occurs the Nisconlith, with an estimated thickness of 15,000 feet, consisting of dark colored argillite-schists and phyllites, showing various stages of alteration from true argillites to micaceous schists. Interbedded layers of dark limestone and quartzite are seen in certain sections. Although the beds yielded no fossils they were referred to the Cambrian by Dawson, because of their relation to the

[1] "On the Geology of the Country between Lake Superior and the Pacific Ocean," James Hector, M.D., 1861, *Quart. Journal Geol. Society*, vol. XVII, pp. 388 to 445.

[2] "Note on the Geological Structure of the Selkirk Range," *Geol. Soc. of Amer.*, vol. 2, 1891, pp. 165 to 176. An extract from this paper is given in Wheeler's *Selkirk Range*, vol. 1, pp. 405 to 409.

crystallines and their supposed equivalency with strata of known Cambrian age in the Rockies to the eastward. The crest of the Selkirks, the region in which occur our snowfields and glaciers, consists of the folded Selkirk series, with an estimated thickness of 25,000 feet and believed to be of Cambro-Silurian age. The strata have been forced into a synclinal fold, which terminates to the eastward by a thrust fault, produced by the western half of a sharp anticline being thrust upward with reference to the eastern half. The rocks consist of gray schists and quartzites, passing into grits and conglomerates which weather to pale yellowish or brownish colors. The latter are often more or less schistose from pressure and other metamorphic agencies, silvery mica, or sericite, being developed. At times the strata are wrinkled and contorted.

Passing into the Rockies, to the eastward, we find them made up very largely of the representatives of the Nisconlith and Selkirk series just described, but known in the report of Dawson as the Bow River and Castle Mountain series. In the western part of the Rockies, adjacent to the Columbia, the upper and younger of the two is continued from the Selkirks, showing crumpling and folding, with metamorphism, but without faulting. The rocks are dipping eastward and have their "strike" parallel with the mountain ranges. Along the center of the range the folds are broad and sweeping, while eastward, for about 25 miles, there is a succession of thrust faults, running parallel with the ranges, the maximum vertical displacement being estimated at 15,000 feet. McConnell made out seven of these faults, giving rise to a series of massive mountain blocks resting in succession upon one another and forming escarpments to the east and relatively gentle slopes to the west. It was to this type of mountain that Leslie Stephen applied the suggestive term "writing-desk."

The ranges making up the central portion of the Rockies are of the Castle Mountain series (Selkirk series) and of Cambro-Silurian age. They are more regular and depart less from the horizontal than the strata to the east and west. Mt. Stephen, on the line of the railway, gives a 5,000-foot section of the series, one shaly band being remarkably rich in Cambrian trilobites. The total thickness of the series is estimated at 10,000 feet, as compared with 25,000 feet in the Selkirks, and consists of limestone and dolomite, with calcareous schists and shales. These rocks give the steep-sided, massive, block-like cliffs, typically shown in Castle Mountain, which has furnished the name for the series. These rocks extend lengthwise of the central ranges to the Yoho Glacier at the north and the Victoria and Wenkchemna glaciers to the south. At the base of Mt. Stephen, at the head of Lake Louise, and in the Bow River, there has been brought up from below by an anticlinal fold the "Bow River Group," or Nisconlith series of the Selkirks. This is of Cambrian age, estimated at 10,000 feet in thickness, and consists of quartzites and conglomerates, with dark gray, purplish, and greenish argillites.

b. Physiographic changes. When viewed from a high elevation the rough ridges and jagged peaks appear to blend, as far as the eye can reach, into a great plateau with a notably even sky-line (pl. 11), giving the appearance of an

General view of Canadian Rockies from summit of Mt. Balfour (10,731 feet), looking west-northwest. Photographed, 1904, by Arthur O. Wheeler and reproduced through the courtesy of the Canadian Topographic Survey. Even character of sky-line signifies an uplifted and dissected peneplain.

uplifted peneplain, similar to that observed by Gilbert farther north in Alaska.[1] The upheaval of such a mass, by lateral pressure, would give rise to troughs and open gaping crevices parallel with the previously formed mountain folds and into these the drainage streams would, for the most part, be diverted. Deepened by stream action, widened by atmospheric agencies, and still further modified by Pleistocene glaciers, we have the longitudinal valleys of the Rockies and Selkirks. The transverse valleys, noted by Dawson as extending into the foot-hills and due to "causes not now apparent," probably mark the location of drainage streams developed while the peneplain was being formed and antedate the final upheaval of the region. That these valleys were occupied by extensive glaciers, presumably in Pleistocene time, is everywhere evidenced by the morainic accumulations, rounded rock contours, glaciated surfaces, extensive plucking, truncation of mountain spurs, amphitheaters, rock basins, and hanging valleys. The valleys generally were filled with ice to a depth of 2,500 to 4,000 feet during the maximum period of glaciation, the height, as pointed out by Wilcox, rarely falling below 7,000 feet above sea-level. Either because the mountains were so completely enveloped in ice and snow, or because of the nature of the final retreat, extensive terminal moraines were not formed in the main valleys. Ground-morainic deposits, however, hundreds of feet thick, occur in places favorable for their lodgment beneath the ice. Near Banff, in the Bow and Cascade valleys, Wilcox discovered evidence of two distinct till-sheets, the older highly charged with pebbles, with little clay, the younger consisting mainly of very hard clay.[2] In the extension of the Bow Valley to the eastward of the mountains, McConnell and Dawson found three separate till-sheets. The lowest and oldest of these appeared to have been entirely derived from the mountains and to pass eastward gradually into the "Saskatchewan gravels" of the plains. For this formation Dawson suggested the term "Albertan,"[3] which he regarded as of pre-Kansan Age.

The upper two boulder-clays contained rock fragments of both eastern and western origin, each variety preponderating in the direction of its origin, showing a commingling of the deposits of the Cordilleran and Hudson Bay ice sheets. The middle of the three till-sheets Dawson correlated with the Kansan and the upper with the Iowan (p. 509). In the light of our present knowledge the upper would be referred to the *Illinoian*, which succeeded the Kansan in the upper Mississippi Valley and was of much wider extent than the Iowan. The correlation of these sheets with those observed at Banff has not yet been made.

c. Lakes. In the very interesting paper above referred to, Wilcox recognizes four types of lakes in those portions of the Canadian Rockies which came under his observation:

First—Lakes lying in depressions of the valley drift, often in chains of

[1] *Harriman Alaska Expedition*, vol. III, Glaciers and Glaciation, Gilbert, p. 183.

[2] "A Certain Type of Lake Formation in the Canadian Rocky Mountains," *Jour. of Geol.*, vol. VII, 1899, p. 249.

[3] "Note on the Glacial Deposits of Southwestern Alberta," *Jour. of Geol.*, vol. III, 1895, p. 510. See also note on page 384, vol. III, *Geology*, by Chamberlin and Salisbury.

three, or four, and especially numerous near the summits of the mountain passes. These lakes show no regularity in form, or location, are usually shallow, and frequently have neither inlet nor outlet.

Second—Lakes dammed by terminal moraines. In the same class may be included those dammed by alluvial cones, or deltas formed in preëxisting lakes.

Third—Lakes lying in rock basins, excavated by former glacial action.

Fourth—A special type of lake, of which Lake Louise is an example, formed just within the mouth of a tributary valley. These lakes are leaf-shaped and from three to ten times longer than they are wide. They owe their existence to the presence of a ridge of ground-morainic material, thrown across the mouth of the tributary valley from the up-stream side and curving gently out into the trunk valley. These ridges have apparently been formed beneath the ice, when the valleys carried glaciers, by the joint action of the tributary and trunk glaciers. The lakes may be shallow and so filled with silt that they are reduced to swamps, or, where the ice was especially active, as in the case of Lake Louise, the depth may still be surprisingly great. As recognized by Wilcox, these lakes may present a combination of the rock-basin and morainic-dam types.

d. Alterations in drainage. In a region of the character above described, exposed for countless ages to the effects of weather, water, and ice, marked alterations in the drainage would be expected, such as reversals, stream capture, and the migration of divides. A study of the Columbia-Kootenay Valley has shown that the upper 200 miles of the Columbia flowed at one time to the south, instead of encircling the Selkirks to the north as at present. This must necessarily have been the case so long as that portion of the valley known as the "Big Bend" was in possession of the ice. The withdrawal of the glaciers into the tributary valleys would permit the present northward flow from the Columbia Lakes while the Kootenay, flowing in the opposite direction in the valley to the east, enters the main valley, approaches within one and one-half miles of the head-waters of the Columbia, but completely skirts the Selkirks to the south before joining it. Upon the opposite side of the Rockies attention has been called by Dawson, McConnell, and Ogilvie to changes in the Bow and its tributaries. The long, slender Lake Minnewanka Valley, near Banff, was evidently the course of a prepleistocene valley that was occupied and modified by an ice stream during the maximum period of glaciation of the region. Dawson considered this to mark the former course of the Bow, which was deflected to the southeastward, along the strike of the soft Cretaceous shales, when the lake valley was occupied by ice.[1] From barometric observations made by Dawson, his assistant McConnell noted that the Ghost River opposite the Devil's Gap, the mouth of the Lake Minnewanka Valley, is considerably higher than the valley floor and concluded that the Ghost River turned and entered the mountains through this valley, joining thus the Cascade and with it forming a tributary

[1] *Annual Report of Canadian Geological Survey for* 1885, "Preliminary Report on the Physical and Geological Features of that Portion of the Rocky Mountains between latitudes 49° and 51° 30′," 1886, p. 141B.

of the Bow.[1] The topographic map of the region, issued in 1902, shows that the river opposite the Gap is fully 100 feet higher than the level of Lake Minnewanka and about 400 feet higher than the present level of the Bow in the vicinity of Banff. According to this view of McConnell the ice-filled Minnewanka Valley compelled the Ghost River to find for itself a new course across the foot-hills to the eastward, which it deepened sufficiently, assisted probably by the ice, to prevent the return of the river into its former course upon the withdrawal of the glacier from the valley. In 1904 Dr. I. H. Ogilvie examined the region and reached the conclusion that the upper Bow and Minnewanka valleys were formerly continuous and that the Bow Valley below Banff was occupied by a stream which cut back into the soft shales until it tapped the upper Bow and effected its capture. She concluded[2] that this had been accomplished in prepleistocene time and that the Lake Minnewanka Valley was occupied by a glacier, fed by hanging glaciers, which moved westward, rather than to the east, deepening the western end of the valley and forming certain morainic deposits about the western end of the lake. The lake itself and its southwesterly drainage would then date from the withdrawal of the ice from the Cascade and Minnewanka valleys. Dr. Ogilvie holds that the drainage in the Lake Minnewanka Valley before the advent of the glaciers was eastward.

The bed of the Bow River at Banff is approximately 4,500 feet above tide, while that of the Ghost River, opposite the Devil's Gap, is not far from 4,900 feet. The present Bow, in the same distance as that from Banff to this portion of the Ghost River, drops 300 feet, so that the bed of the Bow at Banff is some 700 feet lower than it should be in order to have the upper Bow leave the mountains by the Devil's Gap and thence by the lower Ghost River. All will grant that this is too much cutting to expect of the Bow in postpleistocene time and that Dr. Dawson's theory of the diversion of the Bow by the Pleistocene glaciers is untenable. Noting that the Ghost River has also been deepening its bed, with a much steeper gradient and presumably for as long a time as the Bow, the above 700 feet must represent the *excess* of cutting by the upper Bow, when compared with the Ghost, since its capture by the lower Bow, upon Dr. Ogilvie's hypothesis. We have no knowledge of the depth of the drift deposits opposite the Devil's Gap, but there is no reason to think that they would be any deeper there than in the valley of the Bow. The explanation that lies nearest at hand is that of McConnell, *viz.*, that the Ghost River upon reaching the foot-hills made a sharp turn and reëntered the mountains by the Devil's Gap, but was diverted eastward when the Minnewanka Valley became ice-filled. According to this hypothesis the valley of the Ghost from the Gap down should show less maturity than that above the Gap, except so far as it may have been modified by ice action. During the period of maximum glaciation the ice movement in the Minnewanka Valley must have been eastward,

[1] *Annual Report of Canadian Geological Survey* for 1886. Report on the Geological Features of a Portion of the Rocky Mountains, 1887, R. G. McConnell, p. 9D.

[2] "Geological Notes on the Vicinity of Banff, Alberta," *Jour. of Geol.*, vol. XII, No. 5, 1904, pp. 408 to 414.

any tendency towards a westerly movement being checked by the ice in the Cascade and Bow valleys. The westerly movement noted by Dr. Ogilvie was simply a minor episode toward the close of the Pleistocene glaciation.

4. Climatic Data.

a. Geographic distribution of moisture. The climatic conditions of this section of country are peculiarly dependent upon the physiographic features above outlined, combined with its proximity to the Pacific. The centers of the areas of low pressure commonly move in from the ocean to the northward of the region, give rise to westerly winds which convey the warmth and moisture of the Pacific currents across British Columbia and Alberta. At Nanaimo, upon Vancouver Island, separated from the mainland by 30 miles of strait, the precipitation records available show a rain- and snowfall combined ot 41.36 inches, only 5 per cent. of which falls as snow. Opposite, upon the mainland, the total precipitation at Vancouver rises to 63.06 inches, with 4 per cent. falling as snow. This increase is due to the Coast Ranges, having here a northwest-southeast trend, which compel the westerly winds to ascend their westerly slopes, by which rise the air is cooled and its capacity for holding moisture thereby diminished. At Agassiz, in the lower Frazer Valley, the precipitation is but slightly less, although it is located some 70 miles from the Strait of Georgia, up the broad open valley, and about 50 feet above sea-level. Records are available here since 1890, with the exception of the years 1891 and 1899, and give for the 14-year series an average precipitation of 62.02 inches, 6 per cent. of which falls as snow. Over the broad interior plateau which lies between the Coast and Gold ranges, the temperature is colder and the precipitation relatively slight. At Kamloops, with an elevation of 1,160 feet and in latitude 50° 41′, the combined rain- and snowfall averages but 10.66 inches. Passing eastward the air currents impinge upon the westerly slopes of the Gold Range, are again compelled to ascend to still higher altitudes, with the attendant loss of moisture. In consequence, the station of Griffin Lake, located in this range at an elevation of 1,511 feet, and 90 miles east of Kamloops, receives an average precipitation of 34.37 inches, or over three times as much as the latter place. Crossing the Columbia a still higher barrier is encountered in the impressive Selkirk system of ranges, and a correspondingly increased amount of moisture extracted from the still laden air currents. The records in the Selkirks are unfortunately meager, but they indicate a precipitation almost as great as that of Vancouver and Agassiz, and considerably in excess of Nanaimo and Victoria out in the Pacific. The station of Glacier House is located just west of the main crest of the Selkirks, in latitude 51° 16′ and at an elevation above tide of 4,093 feet. The average total precipitation here is 56.68 inches, of which 77 per cent. falls as snow. If the entire amount were precipitated as snow, as is practically the case upon the peaks and elevated névé fields, this would represent an average fall of over 47 feet. This heavy snowfall in the Selkirks and Gold Range has necessitated the erection of numerous snow-sheds over the tracks of the Canadian Pacific Railway, to guard against the frightful avalanches which come crashing down the mountain slopes.

Although Donald is located but a few miles east of Glacier House, it is upon the lee slope of the Selkirks and in the Columbia Valley some 1,500 feet lower. The precipitation here drops to 25.39 inches. The still higher Rockies immediately follow, but the Selkirks have proven greedy and there is relatively little left in the way of moisture. Full precipitation data in the region of the crest ranges of the system are wanting. The snowfall at Field, however, averages about 27 feet, at practically the same elevation as that of Glacier House. If we assume that the same ratio holds here, between snow and rain, as at the latter place the precipitation at Field, lying just west of the main crest, would be about 42 inches. Passing the continental crest the currents are drawn to lower levels, they become warmed by their descent, and their capacity for retaining moisture increases. At Banff the precipitation for the 13 complete years available averages 20.14 inches, of which 39 per cent. falls as snow. Beyond the foot-hills, at Calgary, the precipitation is reduced to 16.64 inches, of which 28 per cent. is snow. The following table furnishes a summary of the climatic data of special interest in connection with this report.

TABLE I.

Climatic Data, from Records of the Canadian Meteorological Service.

Stations, arranged from West to East.	Latitude N.	Longitude W.	Distance from coast, in miles.	Elevation above sea-level, in feet	Mean annual temperature	Highest temperature observed.	Lowest temperature observed.	Average annual precipitation.	Percentage of precipitation as snow.	Number of years in observations.	Remarks concerning location.
Nanaimo	49°10′	123°57′	−30	117	48.7°	90.3°	−3.9°	41.36	5	5	East side of Vancouver Island.
Vancouver	49°17′	123°5′	10	136	48.0°	89.0°	6.0°	63.06	4	4	West slope of Coast Ranges.
Agassiz	49°14′	121°31′	70	52	47.7°	103.0°	−13.0°	62.02	6	14	In open valley of Frazer River.
Kamloops	50°41′	120°20′	270	1160	47.1°	101.0°	−27.0°	10.66	24	10	Interior plateau.
Griffin Lake	50°58′	118°31′	400	1511	44.6°	110.0°	−23.0°	34.37	37	10	Gold Range.
Glacier House	51°16′	117°30′	460	4093	36.9°	89.0°	−21.0°	56.68	77	5	Selkirk System.
Donald	51°29′	117°11′	470	2580	37.4°	97.0°	−45.0°	25.39	51	10	Columbia Valley between Selkirks and Rockies.
Banff	51°10	115°35′	550	4542	35.3°	88.7°	−48.8°	20.14	39	13	East of Continental Divide about 15 miles.
Calgary	51°2′	114°2′	600	3389	37.2°	95.0°	−49.4°	16.64	28	19	Just beyond the foot-hills of the Rockies

Quite in contrast with the still higher mountains of this same system to the south in the United States, the following factors conspire to yield the necessary meteorological conditions for extensive perennial snowfields and glaciers;—

the narrowness of the system, its proximity to the Pacific, the higher latitude, the arrangement of the Cordilleran ranges with respect to height, and the position of the region with reference to the ordinary paths of the great cyclonic areas. If these areas of low pressure commonly crossed the continent so that the path of their centres lay well within the United States, the prevailing winds would be easterly over this region. Such winds would be colder in the winter and warmer in the summer than those which now prevail and capable of supplying relatively little precipitation. There can be but little doubt that any great shifting of the paths of the cyclonic areas, either to the north or the south, would lead to a great reduction in the size of the glaciers of this region, and perhaps to their complete extinction.

b. Chinook winds. One of the most interesting and important climatic factors of this section is connected with the prevailing westerly winds and the north to south trend of the main mountain ranges, giving rise to the so-called "Chinooks." These winds must have been long familiar to the aborigines and voyageurs, but were first noted by Mackenzie about the year 1790 in the region of the Athabasca and Saskatchewan rivers, bringing clear, mild weather in the winter and spring.[1] He ascribed their warmth, very naturally, to the nearness of the warm currents of the Pacific, their progress over the snowfields being assumed to be too rapid to permit of their being cooled. The same winds are known in Montana and still farther south in Colorado, where they are known as "zephyrs" and "snow eaters." They also occur in South America with the passage of westerly winds over the Andes, having been described by Bishop in the vicinity of San Juan, Argentine Republic, under the name "zonda."[2] Here they were supposed to derive their warmth from volcanic sources. The chief characteristics of these, and similar winds are their warmth and dryness and consequent accompaniment of bright sky. They are most conspicuous in the winter and spring, but occur also in the summer and fall. Standing upon the Victoria Glacier, in midsummer, opposite the nose of Mt. Lefroy, one frequently notes gusts of balmy air sweeping down from the elevated snowfields and puzzles over the source of the warmth. The following graphic description of these winds will serve to get before the reader their climatic importance.

"The extreme severity of the winters in certain parts of our northwestern states, among the Rocky Mountains and along their eastern base, is much tempered by the prevalence of a mild westerly wind, locally called the chinook. Its name is derived from that of the tribe of Chinook Indians, living near Puget's Sound. It is said first to have been applied by the early Hudson Bay trappers and voyageurs, who, meeting the wind while travelling towards the Pacific coast, and finding it particularly strong and warm as they approached the lands of this particular tribe, called it the chinook wind.

"It is described as a soft, balmy wind, varying in velocity from a gentle

[1] *Voyages on the River St. Lawrence and through the Continent of North America to the Frozen and Pacific Oceans in the Years* 1789 *and* 1793, London, 1801, p. 138.

[2] *A Thousand Mile Walk across South America.* Boston, 1869. N. H. Bishop.

breeze to a steady gale. Though its temperature rarely exceeds 50°F, yet coming as it does when one is accustomed to a low temperature, it seems warm by contrast with the preceding weather. The thermometer often rises from below the zero point to 40° or 45° in a few hours, and the maximum temperatures of the winter months in the Rocky Mountain region nearly always are coincident with the occurrence of a chinook.

"The sky is usually clear while the warm wind blows, though observers often note a few leaden-colored clouds of a kind seen only during the chinook. These clouds are described as pancake-shaped, with peculiarly smooth, rounded edges, and stand apparently motionless, high above the mountain ranges.

"The continuance of a chinook is as uncertain as its coming. It may last a few hours or for several days. With a change of wind the temperature falls rapidly, and winter weather once more sets in.

"The chinook wind possesses to a remarkable degree the power of melting snow, for it is not only warm, but appears to be dry. Although a foot or more of snow may lie on the ground at the beginning of a chinook, it disappears within a very few hours, often seeming rather to evaporate than to melt. For this reason the chinook is most welcome to the cattlemen on the plains of Montana and Wyoming. In fact, without it, stock-raising would be almost impossible, as the dried grasses of the plains, on which the cattle subsist, would otherwise be buried the greater part of the winter. To a few, however, this wind, instead of being hailed with delight as a break in the cold of the winter, is a source of much discomfort."[1]

The scientific explanation of this type of wind was first given, in part, by the American meteorologist Espy,[2] and later completed by Helmholz, Tyndall, and Hann. Simply stated and adapted to the region under discussion, this explanation may be of interest to many into whose hands this report may fall. The presence of an area of low barometric pressure to the north gives rise to a system of rotary air currents, moving counter-clockwise about the center and constituting a great "whirl." The interposition of mountain barriers, such as those already described, with a north to south trend, compels the winds, which are westerly in the southern portion of the cyclonic area, to mount these obstructions, from the crests and through the passes of which the air is again drawn to lower levels through the suction of the great rotating mass. As the air rises upon the windward slope of the mountain range, it experiences less pressure from the surrounding air, is permitted to expand, and is, in consequence, cooled at the rate of 1° F. for each 180 feet of ascent. This cooling reduces the ability of the air to hold moisture and when the dew-point is exceeded precipitation must result. These facts account for the relatively large precipitation upon the western slopes of the Coast, Gold, and Selkirk ranges. When vapor is condensed there is liberated the so-called latent heat, which disappeared when the water was originally evaporated. It so results that while the air is being cooled by its own expansion, the consequent condensation of its moisture is supplying it with heat, and the actual cooling experienced after condensation begins may be 1° for every 300 to 500 feet of ascent. The amount of heat thus supplied to the

[1] H. M. Ballou: "The Chinook Wind," *American Meteorological Journal*, IX, 1892–93, pp. 541–547.
[2] *Fourth Meteorological Report*, Washington, 1857, p. 147.

ascending currents will obviously depend upon the amount of moisture condensed and the rate at which this condensation takes place. The air will reach the mountain crest at a higher temperature than if no moisture had been condensed; it is capable of retaining more of its moisture in consequence, to be carried to the leeward of the mountain range. In being drawn down the leeward slope of the mountain barrier the air is compressed, as it descends, owing to the greater weight of superincumbent air, and is still further warmed at the rate of 1° F. for every 180 feet of descent. As it is warmed its capacity for holding moisture is thereby increased and it becomes, relatively, more and more dry, although it may actually possess considerable moisture. Such a warm, thirsty wind is our chinook.

The temperature of the air about the peaks and mountain passes differs less in the winter and spring from that of the valleys and lower plateaus, so that the chinook is a more conspicuous feature during these seasons. It is also during these seasons that the cyclonic disturbances are the most pronounced. In the summer and fall the temperature about the peaks and passes is generally sufficiently below that of the lower levels so that, although the heating effect, due to the condensation of vapor and the compression of the air in its descent, may be actually as great, it becomes much less perceptible. During the most favorable season for the chinooks we may, theoretically, account for a sudden rise in temperature of 20° to 25° F., but occasionally it is much greater than this, sometimes amounting to 50°. Mr. E. B. Garriott mentions a rise of 43° in 15 minutes occurring at Ft. Assiniboine, Montana, Jan. 19, 1892.[1] In order to account for such a phenomenon we must postulate a correspondingly high temperature about the crests of the mountains, brought about by excessive and rapid condensation upon the windward slope, or by some other agency. As is well known the temperature about the crests of mountains is often considerably higher than that in the adjoining valley, giving rise to what are known as "inversions of temperature." Since the establishment of the meteorological station upon Sulphur Mountain, October, 1903, with an elevation of 7,459 feet, there have been some 300 such inversions noted up to the close of June, 1906. The following list of some of the most pronounced cases, with dates, is taken from data kindly supplied by Mr. N. B. Sanson, of the Banff station. The upper station is 2,917 feet above the lower and $1\frac{3}{4}$ miles to the south-southwest. Of the 206 instances sent, 163, or 79 per cent. of them, were noted in the morning; 26, or 13 per cent., in the evening, and 17, or 8 per cent., at noon. Of this number 101, or 49 per cent., occurred during the winter months, giving the most pronounced cases of temperature inversion. The spring and fall were each represented by 27 cases, or 13 per cent., while the remaining 51, or 25 per cent., were noted during the summer months.

[1] *Monthly Weather Review*, 1892, p. 23.

TABLE II.

INVERSIONS OF TEMPERATURE, BETWEEN THE BANFF AND SULPHUR MOUNTAIN STATIONS.

Data supplied by the Canadian Meteorological Service.
(Elevation Banff Station, 4,542 feet; Sulphur Mt., 7,459 feet.)

Date.		Time.	Banff Station.	Sulphur Mt. Station.	Difference.
Nov.	17, 1903	6.00 A.M.	—22.6° F.	—14.0° F.	8.6°
Jan.	5, 1904	6.00 A.M.	— 7.4°	16.0°	23.4°
"	" "	6.00 P.M.	— 6.6°	4.0	10.6°
Jan.	17, "	6.00 P.M.	— 1.6°	20.0°	21.6°
Mch.	2, "	6.00 A.M.	—19.1°	4.0°	23.3°
Aug.	26, "	6.00 A.M.	38.5°	44.0°	5.5°
Sept.	2, "	6.00 A.M.	33.8°	40.0°	8.2°
Oct.	25, "	6.00 A.M.	26.6°	35.8°	9.2°
Nov.	24, "	6.00 A.M.	— 1.4°	6.8°	8.2°
Dec.	24, "	6.00 P.M.	— 5.6°	3.5°	9.1°
Jan.	29, 1905	6.00 A.M.	— 7.3°	43.0°	50.3°
Jan.	30, "	6.00 A.M.	—22.2°	1.8°	24.0°
Feb.	3, "	6.00 A.M.	— 9.7°	4.2°	13.7°
Feb.	5, "	6.00 A.M.	—10.2°	10.5°	20.7°
Feb.	11, "	6.00 A.M.	—14.0°	36.2°	50.2°
Aug.	23, "	6.00 A.M.	30.4°	36.0°	5.2°
Sept.	4, "	6.00 A.M.	33.8°	46.0°	12.2°
Nov.	10, "	6.00 A.M.	26.6°	32.2°	5.6°
Dec.	1, "	6.00 A.M.	— 9.5°	2.3°	11.8°
Dec.	31, "	6.00 A.M.	— 6.2°	4.0°	10.2°
Apr.	22, 1906	6.00 A.M.	24.2°	35.8°	11.6°
June	24, "	6.00 A.M.	35.2°	52.0°	16.8°

Geologically the chinooks must exert an influence, the accumulated effect of which may be considerable. They remove much snow from the eastern slopes of the mountains, which might otherwise be available for glacier formation, raising the lower limit of the snow-line and rendering it more irregular. That portion of the melted snow which is not evaporated will course down the mountain slopes as water, accomplishing a different work than if it had remained solid. The alternate periods of thawing and freezing during the winter and spring will accelerate the disintegration of rock upon the eastern slopes of the ranges. By this means glaciers lying to the east of the mountain crests will receive a heavier load of rock débris from neighboring cliffs, talus deposits will be larger than otherwise, and soil formation go on at a more rapid rate. At Innsbruck, in the Alps, where the foehn winds blow upon an average 42.6 days in the year, the mean annual temperature is raised 1.08° F., or the equivalent effect of one degree of latitude.

c. Oscillations in climate. The problem of precipitation has been discussed thus far with reference to its geographic distribution over the region, and although a full discussion cannot be here introduced, there still remains the question of its distribution in time. Here again our data are far too scant for satisfactory generalization, but, so far as the evidence goes, it is in harmony with the theory that precipitation occurs in cycles, there being a series of years in which the total amount is in excess of the normal, although it may fall below for some particular year of the series. This damp phase of the cycle is followed by a series of years during which the total amount of precipitated moisture is less than the normal for this number of years, although it may be in excess for some particular year. Based upon the meteorological data from 321 stations distributed over Europe, Asia, Africa, Australia, North and South America, Brückner discovered the length of the cycle to be 35.5 years,[1] the dry phase averaging slightly longer than the damp one. At neighboring stations the cycles may partially overlap and, in the case of coast regions, the phases may be completely reversed, as recognized by Brückner. Coincident with the damp phase there is a general reduction in temperature, an increase in the level of lakes and rivers, a rise in the ground-water level, a halting or advance of the front of glaciers. The following table shows at a glance such data as are available along these lines, compiled from publications of Heim, Richter, Brückner, and Hess. The glacial data refer mainly to the Alpine region. Constructed for any particular region the figures would necessarily differ more or less from those given. So far as the United States is concerned the dry phase through which we have just passed appears to have closed and we are entering upon another series of damp years. In the Canadian region under study the damp phase seems to have started about three or four years earlier than in the Great Lake region and the preceding dry phase about as long before.

TABLE III.

PERIODIC OSCILLATIONS OF CLIMATE, WITH THEIR EFFECTS UPON LAKE LEVELS AND ALPINE GLACIERS.

PRECIPITATION.		TEMPERATURE.		LAKE LEVELS.		GLACIERS.	
Damp.	Dry.	Cool.	Warm.	High.	Low.	Advancing.	Retreating.
1591–1600		1591–1600				1595–1610	
			1601–1610				
1611–1635		1611–1635				1630	
			1635–1645				
1646–1665		1645–1665				1677–1681	
			1665–1690				
1691–1715		1691–1705				1710–1716	
	1716–1735		1706–1735		1720		
1736–1755		1731–1745		1740		1735	
	1756–1770		1746–1755		1760		1750–1767
1771–1780		1756–1790		1777–1780		1760–1786	
	1781–1805		1791–1805		1798–1800		1800–1812
1806–1825		1806–1820		1820		1811–1822	
	1826–1840		1821–1835		1835		1822–1844
1841–1855		1836–1850		1850		1840–1855	
	1856–1870		1851–1870		1865		1855–1875
1871–1885		1871–1885		1880		1875–1893	
	1886–		1886–		1892		1894–

[1] *Klima-Schwankungen seit* 1700, Edward Brückner, Wien, 1890, pp. 133–193.

Numerous factors conspire to prevent the movements of glaciers from being exactly coincident with the corresponding climatic phases. For the Swiss glaciers Heim found that, ordinarily, an advance began from 3 to 6 years after the opening of a damp-cool phase and reached its maximum in 4 to 10 years, but in the case of the longest glaciers the maximum position might not be reached until the close of the cycle itself. These facts partially explain the anomalous behavior often noticed in neighboring glaciers. When the Illecillewaet Glacier was first visited by the Messrs. Vaux, in 1887, it was standing close up against a small moraine, which it had just formed, or more probably assisted in forming during this period of halt. Since 1887 this glacier has been in constant retreat at an average rate of 33.2 feet per annum. In 1905 the retreat was found to have been reduced to 2 feet and the inference is that the glacier is preparing to advance. So far as we may judge from a study of this one glacier, the best known of the series, a damp-cool phase of the precipitation cycle closed in the early 80's, and was followed by a dry-warm phase, which lasted for 16 to 18 years, ending somewhere near the close of the century. The following quotation from Dawson furnishes confirmatory evidence of the existence of the preceding wet phase of the cycle, which was itself preceded by a dry phase.[1]

"Evidence of a remarkable character has been found, which tends to show that a somewhat rapid increase in the total annual précipitation, has taken place during late years, and deserves to be recorded here. The evidence referred to is that afforded by the abnormal height of small lakes, without outlets, occurring in regions characterized by moraine hills. These serve as natural gauges, but instead of measuring the actual rainfall give a result, dependent on this and the counteracting effect of evaporation. The abnormal character of the rise of the water in these lakes is shown by the facts that it has killed a belt of trees, some of large size, and at least fifty years in age, along parts of the margins of some of these lakelets. Both the Douglas fir and the yellow pine—the latter, never naturally growing even in damp soil,—have been found in numbers thus killed. The condition of the trees shows that they have been killed within a few years, and their size indicates that the waters of the lakes in question have not been for any considerable time during a period of 50 years or more, at the present high level. These observations were made in both 1883 and 1884. The lakelets observed to be so affected were numerous and scattered over a belt of country along the western part of the range [Rockies] for a length of about 140 miles."

Looking to the records of the Canadian Meteorological Service for still further evidence of the periodicity of the climate of the region, we find that only three of the stations have records sufficiently continuous and reaching far enough back to be of help. These stations are Agassiz, Banff, and Calgary and their averages are more nearly the real, but still unknown, normal. Average annual temperatures and precipitation for the mountain stations, based upon observations made between 1880 and 1897, will certainly be found later to be too high for the temperature and too low for the precipitation, while those averages based upon observations taken since 1897 will prove to yield too high a precipitation and too low a temperature. In table IV we place side by side the

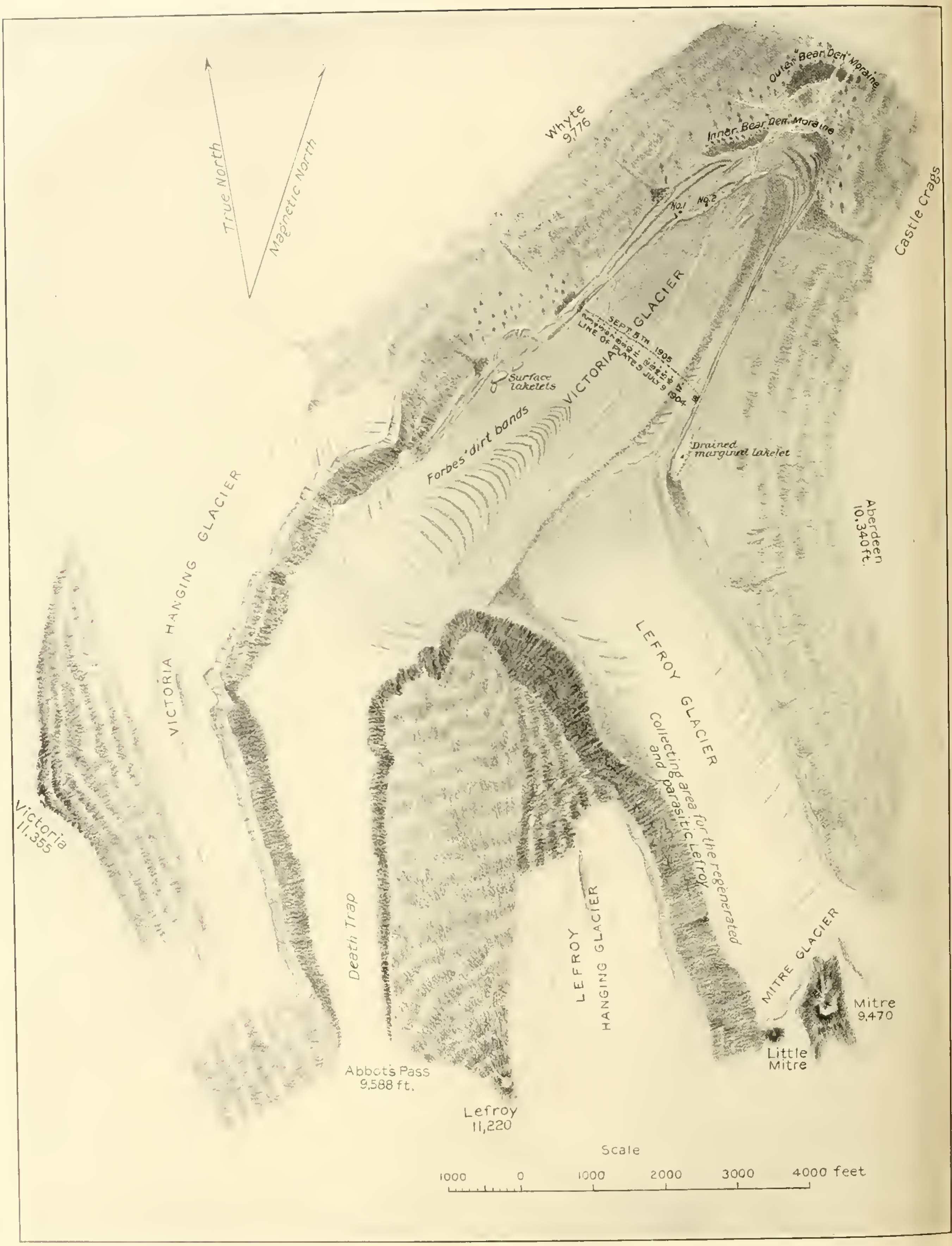
[1] *Geological Survey of Canada for* 1885, p. 32 B.

precipitation data for the above three stations, so far as such data are obtainable. In the first column for each station is given the total precipitation, in inches, the snowfall being reduced to rain upon the supposition that 10 inches of snow are equal to one of rain. In the second column is given, for each year, the actual deficiency, or excess, when the amount is compared with the *normal*, or average for the entire series of years. In the third column the actual precipitation appears as a *percentage* of the normal, while in the fourth there is given the *accumulated* excess, or deficiency, to or from the beginning of the year 1897. So far as we may be permitted to draw conclusions from all available data, the break between the damp and the dry phases of the precipitation cycle in this region occurred about 1897 in the Rockies and 1898 in the Selkirks and we may venture to predict that for another decade the precipitation will be in excess of the true normal for the various mountain stations. An examination of the Agassiz data, from the lower Frazer Valley, shows that while Banff and Calgary were deficient, this station was accumulating an excess and that since 1897 there has been a marked deficiency. The inference is that we have here an example of one of Brückner's exceptional coast regions, in which, although the precipitation is also in cycles, the crests of the great waves correspond with the troughs over the general surface of the earth. It is very unfortunate that the data from Vancouver, Nanaimo, and Victoria are not full enough to show whether or not they are included in this region.

TABLE IV.

Precipitation Data, by Years, for Calgary, Banff, and Agassiz.

Year.	Calgary. Total precipitation.	Calgary. Excess or deficiency.	Calgary. Percentage of normal.	Calgary. Accumulated excess or deficiency.	Banff. Total precipitation.	Banff. Excess or deficiency.	Banff. Percentage of normal.	Banff. Accumulated excess or deficiency.	Agassiz. Total precipitation.	Agassiz. Excess or deficiency.	Agassiz. Percentage of normal.	Agassiz. Accumulated excess or deficiency.
1885	12.91	−3.73	78	Accumulated deficiency 36.01 in.				Accumulated deficiency 17.80 in.				Accumulated excess 29.80 in.
1886	11.32	−5.32	68									
1887	15.69	−0.95	94									
1888	17.41	+0.77	105									
1889	11.59	−5.05	70									
1890	15.47	−1.17	93		19.54	−0.60	97		56.43	−5.59	91	
1891					16.48	−3.66	82					
1892	7.91	−8.73	47						67.78	+5.76	109	
1893	11.05	−5.59	66		10.88	−9.26	54		76.95	+14.93	124	
1894	11.63	−5.01	70						78.01	+15.99	126	
1895	16.00	−0.64	96						54.50	−7.52	88	
1896	16.05	−0.59	96		15.86	−4.28	79		68.25	+6.23	110	
1897	20.58	+3.94	124	Accumulated excess 35.97 in.	23.40	+3.26	116	Accumulated excess 17.83 in.	63.43	+1.41	102	Accumulated deficiency 29.76 in.
1898					20.58	+0.44	102		50.31	−11.71	81	
1899	26.15	+9.51	157		26.34	+6.20	131					
1900	17.57	+0.93	106		23.29	+3.15	116		72.00	+9.98	116	
1901	22.31	+5.67	134		19.27	−0.87	96		52.98	−9.04	85	
1902	34.57	+17.93	208		30.59	+10.45	152		54.68	−7.34	88	
1903	22.77	+6.13	137		24.82	+4.68	123		57.74	−4.28	93	
1904	10.82	−5.82	65		14.80	−5.34	73		54.67	−7.35	88	
1905	14.32	−2.32	86		16.00	−4.14	79		60.59	−1.43	98	
Normal	16.64				20.14				62.02			



Map of Victoria Glacier, Lake Louise Valley, Canadian Rockies. Surveyed and drawn by W. H. Sherzer, July, 1904. Field assistants De Forrest Ross and Frederick Larmour. Adjacent regions based upon maps of A. O. Wheeler and D. W. Wilcox.

CHAPTER II.

VICTORIA GLACIER.

1. General Characteristics.

The Victoria Glacier originates at Abbot's Pass, upon the crest of the Great Continental Divide which separates British Columbia from Alberta, flows due north for a mile between the precipitous walls of Mts. Victoria and Lefroy, makes an abrupt turn to the northeast and pursues a straight course for another two miles before wasting away in the Lake Louise Valley. The collecting area at the Pass is much restricted and narrows down to 600 to 700 feet, where the rocky cliffs upon either side begin to frown at each other from beneath the snow. These cliffs become higher and separate gradually, allowing the glacier to broaden to about one-third of a mile as it approaches the bend in its course. Rounding the nose of Mt. Lefroy the glacier receives its double tributary from the southeast, attains its greatest breadth of one-half mile, and for the last mile narrows regularly to its débris-covered nose. In this lower third of its length it lies between Mt. Aberdeen (elevation 10,340 feet) and Castle Crags upon the east and Mt. Whyte (9,776 feet) upon the west. A general view of the lower two-thirds of the glacier, with the tributary entire, is shown in plate IV, figure 1, while plate IV, figure 2, shows the upper portion and gives a lengthwise view of the tributary.

A Watkin mountain aneroid was carried to the crest of the Pass, July 22, 1904, and gave an elevation, when corrected, of 9,370 feet above sea-level. The more accurate methods of the Canadian Topographic Survey gave Wheeler 9,540 feet elevation for this same Pass, from which the descent through the so-called "Death-Trap" is rapid, requiring the cutting of steps in the snow when it is hard from freezing. Owing to the north-south direction of this part of the valley and the height of the bounding cliffs, the sun has little direct power and the glacier is permanently covered with snow which assumes a granular form, owing to the partial melting of the flakes, and constitutes the névé. This condition of the snow causes it to resemble granular tapioca and may be seen in the snows which, in more southern latitudes, linger until late in the spring. The névé-covered portion of the Victoria reaches an altitude of about 7,500 feet, or about 2,000 feet below the Pass, when, as the glacier turns to the northeast, the ice makes its appearance through the snow. The line of separation between ice and snow, as seen at the surface, is irregular and uneven, shifting with the season and from year to year. Winters of scanty snowfall, followed by bright warm summers, will send the névé line up the glacier; while winters of heavy snowfall and cool summers will cause this line to move toward the nose. Plate V, figure 2, shows the upper third of the glacier, leading to the Pass through the "trap," and the névé line in the foreground, as it appeared in July, 1904. Rounding Lefroy, the glacier descends rather abruptly some 400 to 500 feet, owing apparently to a sudden change in the inclination of its bed, giving rise to a series of transverse crevasses. The lower one and one-half miles of the Victoria presents a remarkably even surface slope, suggestive of a correspondingly even bed, so that it may be ascended with entire safety by the most inexperienced. The nose reaches an altitude of about 6,000 feet, so that the average slope is at the rate of about 1,200 feet to the mile. For the lower half the surface slope is but 650 to 700 feet to the mile, or at the average rate of 7° to 8°.

In the névé region the surface of the glacier is concave, owing to the accumulation of snow along the base of the cliffs, this being permitted by the relatively small amount of heat radiation and reflection. For a short distance opposite Lefroy the cross sections of the ice stream have a horizontal surface line, while in the lower portion the surface is flatly convex, owing to the lateral melting caused by the rock walls and, to a greater or less extent, by the lateral drainage streams. (See the cross-section of the Victoria along the line of the steel plates, page 30.) It does not seem probable that the glacier attains any considerable thickness, the thickest portion, apparently, lying opposite the tributary where the ice may be 500 to 600 feet in depth. The nose is rounded, completely veneered by rock débris so as to conceal the ice, and perched up above the valley floor upon an old moraine which it has partially overridden, but has not had the strength to push aside (plate v, figure 1). The front here is steep, the angle being about 38°, and about 90 feet in height, with a series of gradually rising crests from the medial and right lateral moraines. Back from this nose some 2,000 feet, there is exposed a steep ice wall, 35° to 50°, which attains a height of 125 feet, and continues for about 800 feet. This now appears as the *side* of the glacier, but the position and form of the older moraines show that the front has been gradually swinging around into this oblique position, the cause of which is apparent from an inspection of the map. The eastern side of the glacier is much better protected by the right lateral moraine and by the much broader and closely placed medial. This portion of the front is thus prevented from melting, while the less well protected western half has been rapidly receding. Between this oblique ice wall and the real nose other smaller faces are developing and being enlarged with each season's melting.

2. Nourishment.

The main glacier is nourished in four ways, which may be separately recognized, as follows:

a. By the moisture directly precipitated into the valley between Mts. Victoria and Lefroy. The great bulk ot this is in the form of snow, which probably amounts to about 25 feet per annum. The lesser amount in the form of hail, rain, dew, fog, and frost would also contribute to the substance of the glacier.

b. The funnel-like form of the valley, with its opening to the north, enables it to catch and retain large quantities of snow drifted southward by the north winds, as well as that which collects in the lee of Victoria when a west wind is

Mitre. Lefroy. Victoria.

FIG. 1.—General view of Victoria Glacier looking southward.

Mitre. Lefroy. Abbot s Pass. Victoria.

FIG. 2.—Lefroy Tributary. Victoria Glacier.

FIG. 1.—Débris-covered nose of the Victoria Glacier. July, 1904.

FIG. 2.—Névé field of Victoria Glacier, looking southward through "death trap." July, 1904.

FIG. 1.—Path of an avalanche along Victoria névé. Photographed by De Forrest Ross, July, 1904. Note ice levees along the margin of the path.

FIG. 2.—Hanging glacier upon Mt. Victoria as seen from summit of Mt. Aberdeen (elevation 10,340 feet). Photographed, 1903, by Arthur O. Wheeler.

blowing, or in the lee of Lefroy with an east wind. Thus because of its shape, position, and depth the upper valley is able to capture much more snow than it would ordinarily be entitled to.

c. Upon the opposing faces of Victoria (elevation 11,355 feet) and Lefroy (11,220 feet) large beds of snow accumulate during the fall, winter, and early spring. During the late spring and early summer much of this snow is precipitated into the valley as avalanches, with the roar of thunder and the blast of a tornado. It is the danger from this source that has suggested the name "Death-Trap," for the narrower portion of the valley, although no fatalities have yet occurred here. These avalanches may shoot directly across the valley, or they may turn and move along it lengthwise as shown in plate VI, figure 1. They must bring down numerous rock fragments, which are distributed completely across this portion of the glacier and incorporated into its névé.

d. A considerable portion of the snow which clings to the eastern shoulder of Mt. Victoria is compacted into stratified ice, and over an area of about one square mile there arises a true glacier perched up on the mountainside, with a slope that appears too steep to give it a foothold. Such a glacier is known as a "cliff glacier," or "hanging glacier" (plate VI, figure 2). It moves down the slope, probably with considerable velocity, and is avalanched into the valley upon the back of the Victoria Glacier, filling the air with ice dust. At the crest of the precipice the ice has an estimated thickness of 200 to 300 feet, from which great blocks, sometimes as large as a city square of buildings, are detached and fall vertically 1,200 to 1,500 feet. At certain places where the falls are more frequent there are built up débris cones of coarse granules upon the western margin of the glacier. This avalanched ice spreads over the glacier and is incorporated into its body along with more or less ground-morainic material which has been manufactured between the hanging glacier and its bed. When the weather is cool and cloudy these ice avalanches are infrequent, but upon a warm bright day, with much melting and more rapid forward movement of the ice, they occur every few minutes from some portion of the long front. On August 25, 1903, during the mid-portion of the day avalanches were noted as follows:

10:39 A.M.	moderate.	12:29 P.M.	moderate.
10:43	slight.	12:49	moderate.
11:05	slight.	12:52	slight.
11:27	slight.	1:11	moderate.
11:28	heavy.	1:18	moderate to heavy.
11:40	slight.	1:35	moderate.
12:20 P.M.	slight.		
12:27	moderate.	1:52	moderate.
		2:10	moderate.

Owing to its western and southern exposure the opposite face of Lefroy does not support a hanging glacier, although there is a suitable collecting area for the snow. That which is not precipitated into the valley as avalanches melts away in the course of the summer and this water, along with that from Mt. Victoria, forms slender cascades, which are partially absorbed by the névé and, in part, work their way to the bed of the valley and are incorporated into the subglacial drainage. In these various ways the upper Victoria receives the precipitation from about two square miles of collecting area. Through pressure, rain, and surface melting, due to the intense solar action, as well as the chinook winds, this mass of granular snow is compacted into a very fine granular ice. Powerful winds sweep over the bare peaks and ridges and spread over the névé more or less fine matter, organic as well as inorganic. This material is concentrated at the surface, when sufficient melting has taken place, and gives a rather sharp line of demarcation between the older snow and that which falls freshly upon it. In consequence of the melting and the presence of the foreign matter, the névé acquires a characteristic stratification, which in the case of the Victoria persists to its nose. Owing to the avalanches of snow and ice from Mts. Victoria and Lefroy these strata are rendered more or less irregular. The great weight of this snow and underlying ice forces the entire mass valleyward and thus prevents indefinite accumulation.

3. Double Tributary.

a. Mitre Glacier; the host. Upon either side of the small peak known as the Mitre (elevation 9,470 feet), there descend two steep snow slopes, which give rise to two névé-covered streams of ice (see plate VII, figure 2). That to the right is intersected by a great crevasse, caused by the glacier drawing away from the snow and ice which adhere to the rocky slope, and forming what is known as the "bergschrund." This schrund renders this stream impracticable, but the other may be safely ascended with a guide, to the Mitre Pass leading over into Paradise Valley. Here from an elevation of 8,480 feet the descent is very rapid for about 1,200 feet, when the two streams unite into a single glacier, for which the name Mitre, first proposed by Allen for the entire tributary, may best be retained. For a very short distance the glacier is permanently covered with névé, but in midsummer this soon disappears and discloses a very weak and poorly defined medial moraine (plate VII, figure 2). It flows lazily down the straight valley, one and one-third miles, between Mts. Lefroy and Aberdeen, attains an average width of one-third to one-half a mile, and joins the Victoria with a breadth of 3,200 feet.

b. Lefroy Glacier; the parasite. Upon the eastern and northern slope of Mt. Lefroy, because of its exposure and other favorable conditions, there has arisen another hanging glacier similar to although smaller than that just described upon Mt. Victoria. Plate IV and plate VII, figure 1, give views of this elevated glacier, clinging to the steep mountain slope, the latter view being taken from the summit of Mt. Aberdeen, looking westward and from an elevation of 10,340 feet. From the steep, vertical ice face great blocks are avalanched 2,000 feet into the valley, much of the ice being ground into dust and shot

FIG. 1.—Hanging glacier upon Mt. Lefroy as seen from summit of Mt. Aberdeen (elevation 10,340 feet). Photographed, 1903, by Arthur O. Wheeler.

Aberdeen. Mitre Pass. Mitre. Little Mitre. Lefroy.

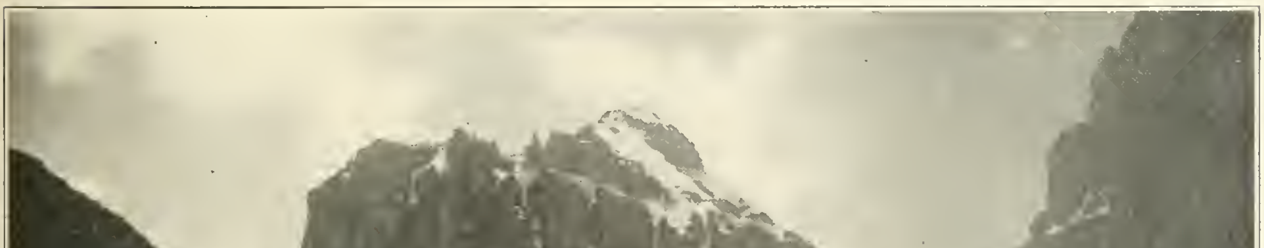


FIG. 2.—Double névé field of Mitre Glacier, July, 1904. Faulted névé strata are seen in left tributary and a bergschrund in the right. In foreground a snow-filled crevasse; beyond which lies the névé line.

out beyond the base of the cliff. Upon the western or Lefroy side of the upper half of the Mitre Glacier, there is thus heaped up a mass of pulverized ice, which is compacted by freezing into strata. This mass constitutes a new glacier, since the structure of the original one must have been destroyed by the plunge, with the exception of the granules and their fragments. Such a glacier is said to be "reconstructed," or "regenerated." Furthermore, this new glacier rests upon the back of the Mitre; is nourished differently; is of a different form; has its own distinct set of strata, unconformable with those of the Mitre; moves across the valley instead of lengthwise of it, and is accomplishing a totally different geological work. This glacier, for which the term Lefroy is appropriate, is one of the best known examples of what Forbes termed a "parasitic glacier,"[1] far better, indeed, than the type itself. It is parasitic in the sense that it is carried by its host, the Mitre, and in that it is nourished entirely by snow and ice which would be otherwise available for the host.

Just what is the structural relation of the Lefroy to the Mitre, the parasite to its host, can only be conjectured, since the contact was not observed and the plane of separation may not be at all distinct. There is, however, a very evident, deep-seated motion down the valley and an equally evident superficial motion across from the base of Lefroy to the foot of Aberdeen. The result of the latter motion is to carry most of the ground-morainic material, such as clay, sand, bruised and scratched pebbles and boulders, which has been manufactured beneath the hanging glacier of Lefroy, entirely across the valley and dump it in a great heap upon the eastern or Aberdeen side of the Mitre (plate VIII, figure 1, and plate XV, figure 1). The *front* of the parasitic Lefroy being parallel with the *side* of the Mitre, some of the ground-morainic deposit is arranged in ridges parallel with the side of the latter, in which form it is being dealt out to the Victoria. Until the above stated relations were discovered it was a serious puzzle to ascertain how a glacier could get its ground moraine upon its own back and arrange it in ridges parallel with its side (see plate XV, figure 1). That the material could not have come from Mt. Aberdeen was evident from the fact that it does not support a hanging glacier upon its western face, as shown in plate VIII, figure 2, although there is a buried mass of stagnant ice upon the northern shoulder. Avalanches of snow and the ordinary processes of weathering have brought down considerable angular material from Aberdeen which covers most of the ground-morainic deposit from the opposite side of the valley. While this ground-morainic material is being moved east-northeast by the Lefroy for a distance of 1,800 to 1,900 feet, it is also being carried north-northwest for a distance of about 3,800 feet by the underlying Mitre and the resultant motion is somewhat east of north. This will be made clear from an inspection of the map, plate III.

Opposite the large débris cone seen in plate IV, figure 2, upon the western side of the Lefroy Glacier, there is a marked depression in the surface of the ice and also across the entire tributary where it joins the Victoria, giving good

[1] *Travels through the Alps of Savoy*, James D. Forbes, Edinburgh, 1845, p. 201.

exposures of the outcropping edges of the strata, to be noted later. These depressions furnish confirmatory evidence that the general movement of the superficial layers is *across* and not parallel with the valley. The position of the left lateral moraine from the débris cone, above noted, to the Victoria, shows, however, that along the base of the Lefroy cliff the movement is normal and due to the Mitre, although the strata belong to the Lefroy. In consequence of this a relatively small amount of morainic material is captured from the Lefroy and delivered to the medial moraine of the Victoria at the nose of Mt. Lefroy. This double tributary joins the Victoria at an elevation of about 6,670 feet, having an average surface slope of 1,360 feet to the mile, and is at once compressed to about 600 feet, as compared with 3,200, or as $5\frac{1}{3}$ is to 1. There being no corresponding increase in the height of the ice, the inference is that the tributary delivers relatively little ice to the Victoria and that its movement is correspondingly slow.

4. Drainage.

a. Surface ablation. The drainage supply of the glacier originates from the rainfall over the glacier and adjacent mountain slopes, from the melting of the snow and ice in the region of the hanging glaciers, and from the general melting of the glacier itself and its tributaries. No definite data are available concerning the rainfall over the glacier and adjacent slopes. Owing to its greater altitude it would be much less than at Field and Banff and would practically all fall during June, July, August, and September. After heavy showers the streams from the mountain slopes are in many cases highly charged with sediment, those originating from the melting of snow being generally clear.

The temperature of the ice during the summer was found to be either just at the freezing point, or so near it that any addition of heat was sufficient to start the process of melting. In the abandoned drainage tunnel, to which reference will be made later, holes were bored into the ice wall, 140 feet back from the entrance, and a standard minimum thermometer inserted its full length. Owing to the course of the tunnel the point of observation was estimated to be 70 feet from the foot of the oblique ice wall and about 17 feet from the actual ice face (plate VIII, figure 4). During the week from July 31 to August 7, 1904, the readings were 31.8° F., 31.6°, 31.8°, 31.9°, 31.7°, and 32°. The maximum temperature of the air in the tunnel during the week ranged from 31.4° to 33.0° F. Owing to the warmth of the body and that of the candle used, it was found impracticable to get the temperature of the air at the same time that the temperature of the ice was taken.

In the rarified atmosphere at these high altitudes the midsummer sun strikes with surprising force and the surface ice, so near its melting point, is at once converted into water without changing its temperature. In the case of scores of observations made upon the surface streams of the series of glaciers the temperature was almost uniformly 32° F. In rare cases it was found to be a small fraction of a degree above. In order to secure some data for an estimate

Aberdeen. Mitre. Lefroy

FIG. 1.—Parasitic Lefroy Glacier being carried by Mitre Glacier. Morainic accumulation at base of Mt. Aberdeen consists mainly of *ground* moraine, manufactured beneath the hanging glacier on Mt. Lefroy and carried across the Mitre by the Lefroy.

FIG. 2.—Western face of Mt. Aberdeen, looking across Lefroy Glacier from surface of the Victoria.

FIG. 3.—Surface drainage stream upon Victoria Glacier.

FIG. 4.—Oblique front of Victoria Glacier, showing abandoned drainage tunnel. July, 1904.

of the rate at which surface ablation was taking place over the lower portion of the Victoria, accurate elevations were taken upon the series of steel plates used in determining the forward movement. The results are shown in table V, page 31, giving the total melting from July 13 to August 4, 1904, for a period of 22 days of midsummer. The maximum lowering of the ice surface occurred at plate No. 13, nearly two-thirds of the way across when measured from the west side, and amounted to 3.8 feet, or a daily average of 2.076 inches. This plate was located on a portion of the glacier least protected by rock débris. Although this lowering of the surface is due, in the main, to the sun's action and general effect of the atmosphere, usually above the freezing point in summer, there are other minor agencies which would tend to give the same result. One of these is the rain, 1.506 inches of which fell during the period of the observations. Other agencies are subglacial melting and subglacial erosion, longitudinal stretching, or a lateral spreading of the ice, all of which would tend to lower the upper surface. It should be noted, further, that in the 22 days this plate moved forward 60 inches and with the average surface slope of 7° to 8°, the plate would be lowered by this agency alone about one-third of an inch daily. Making this correction the actual ablation, from sun, atmosphere, and rain, would amount to about 1.74 inches daily and for the two main months of July and August would give a total of about 9 feet. Observations upon the lower Lefroy showed that the ice surrounding certain morainic heaps had been lowered during the season by about this amount. No glacial tables of this height can be found, however, because of the undercutting effect of the sun's rays and the consequent destruction of their pedestals. The broad medial depression lying just west of the medial moraine (see plate IV, figure 2, and cross section page 30) has been produced by the greater surface melting and this has been permitted by the thinner covering of rock débris, the ice of this portion of the glacier coming from the Lefroy side of the upper Victoria. This depression continues down the glacier for 2,200 feet, where it thins out, apparently from surface melting. With a forward motion here of about 64.5 feet annually, it would require 34 years for the ice to move from the line of plates to the oblique ice face, during which time some 306 feet of ice might be melted away. If the rate of melting and rate of forward movement remained constant, this number would represent the approximate thickness of the ice beneath plate 13. It is very probable that the rate of melting becomes less, owing to the concentration of rock débris at the surface, but it is also very probable that the rate of forward movement becomes also less as the ice diminishes in thickness. The work with the spirit level indicated that this plate was originally 393 feet above the lower margin of the ice in this depression, the difference of 87 feet representing the rise of the valley floor in this distance. If this latter figure is approximately correct the inclination of the bed is much less than that of the surface of the ice itself

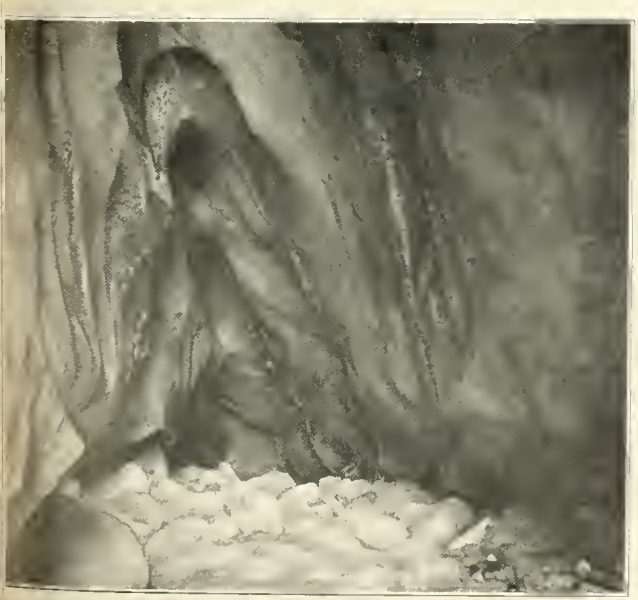
b. Surface drainage. Over the entire névé area the water from the melting snow, as well as that from the rainfall, is absorbed into the body of the glacier and refrozen, binding the granules together into an ice conglomerate. Where the ice itself is exposed and crevasses absent, the melted ice and rainfall are concentrated into more or less well defined channels, which persist from season to season. In the early morning the glacier is impressively quiet, the ice is dry, and many of the small pools are frozen over with a thin layer of ice. When the summer sun enters the valley the exposed ice becomes moist, small trickles of water unite into rills, that grow larger and larger from the union of innumerable others, and these form still larger brooks which empty their clear, ice-cold waters into the main drainage channels and, after a day of rapid melting, we have here roaring torrents. These streams slowly cut their way into the solid ice by mechanical erosion, assisted by the rock fragments which the water is able to move along, and by melting. The water being apparently at the melting point of the ice, 32° F., it is incapable of imparting heat to that over which it flows and the melting must arise from the conversion of its kinetic energy into heat. Such heat would be imparted to the ice, rendered latent in the process of liquefaction and the temperature of the water would not be sensibly raised. The question arose in the mind of the writer while studying these ice streams whether water at 32° is capable of *dissolving* ice at the same temperature, as it might dissolve rock salt over which it was flowing. So far as he has been able to learn the question has not been investigated, but if water does have any such effect upon ice under these conditions, it would help to explain the formation of these ice channels.

In the upper part of their courses these stream beds are generally free from débris and quite straight, but as the bed is broadened, boulders, too large for the stream to handle, slide in from the surface and the stream is compelled to go around. In this way a system of meanders is formed, as shown in plate VIII, figure 3, and the ice banks are rendered steep and, here and there, undercut by the rushing water. In the lower portions of the course the bed may contain considerable rock débris, but this has simply slid down from the surface and nowhere suggests an aggrading action of the stream. When the stream channel is contracted for any reason, the level of the water is raised, its velocity increased in consequence, and an ice basin cut out upon the down-stream side, filled with more quiet water. This is suggestive of the manner in which the Lake Louise rock basin, to be later described, may have originated when the entire valley was ice-filled.

In portions of the glacier intersected by crevasses it is obvious that surface streams, of any considerable size, cannot develop. The water escapes by an englacial or subglacial tunnel, to reappear at or near the nose. When a stream encounters such a crevasse, from which there is drainage beneath, it forms a small cascade and begins to cut a channel in the vertical face of the crevasse wall. If the velocity and volume of the water are sufficient, a corresponding channel may be produced in the opposite wall. As the lips of the crevasse are subsequently brought together by movements of the ice body, and the crevasse is healed, this small vertical channel persists and still furnishes an

FIG. 1.—First stage in formation of a moulin, Lefroy Glacier.

FIG. 2.—Marginal lakelet west side Victoria Glacier.



[FIG.] 3.—Inner end abandoned drainage tunnel, Victoria Glacier, July, 1904.

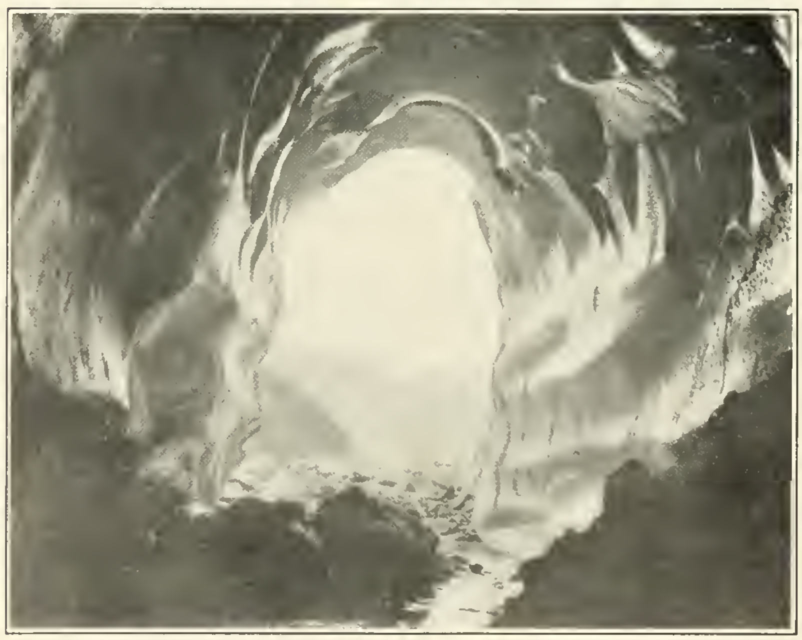


FIG. 4.—Mouth abandoned drainage tunnel, Victoria Glacier, looking outward. July, 1904.

escape for the surface stream. This is well shown in plate IX, figure 1, the small stream entering the nearly healed crevasse from the right. As the ice moves valleyward the drainage area of the stream may be enlarged, the amount of water correspondingly increased, and our glacial well, or "moulin," may be indefinitely enlarged both in diameter and depth. Since the water is introduced from above and escapes below, they are more like *wells*, turned wrong-side up. They may be found in various stages of development, the younger in the region of the open crevasses, the mature examples in the lower course of the glacier, where they have been carried by the general forward movement of the ice, and into which the surface torrent plunges with a sullen roar to unseen depths.

The main drainage stream of the Victoria Glacier starts near the nose of Mt. Lefroy, to the west of the medial moraine, and passes somewhat obliquely downward to a moulin, opposite the oblique ice face (plate IV, figure 1, and plate III). This stream drains that portion of the glacier over which the surface melting is the greatest. A second drainage stream originates near the above, but in the depression between the medial moraine and the Lefroy tributary. This stream collects the surface waters from the tributary and extends for one-quarter mile down the deep depression between the medial and right lateral moraines and disappears in a system of crevasses that cut this portion of the glacier.

Two short, but rather deep, drainage channels occur upon the western side of the glacier, lying upon the inner side of the left lateral moraine. One of these has incised the ice to a depth of 18 to 20 feet. Since these streams have probably occupied their present sites for many years it is rather remarkable that they have not completely cut through the ice to the rocky bed beneath. From the fact that they have not done so we are forced to conclude, either that the rate of cutting is surprisingly slow, or else that the glacier thickens in such a way that the bottoms of the streams are elevated with reference to the base of the glacier. It is possible that the longitudinal compression to which the glacier is subjected in its lower half may be sufficient to secure this result.

c. Marginal drainage. Upon the eastern side of the lower Victoria, along the base of Mt. Aberdeen and Castle Crags, there is no visible marginal drainage at present, but water may be heard trickling amongst the rocky débris. Just at the head of this depression, however, where the tributary joins the main Victoria, there is evidence of earlier drainage here, in the form of an abandoned lake bed, with a length of 500 to 600 feet. A small gravel delta was formed at the head, while the rest of the bed is filled with silt. A still smaller lakelet existed for a short time at the nose of Mt. Lefroy, in the depression between this side of the tributary and the Victoria. Upon the western side of the glacier there occurs a similar marginal lakelet, between the glacier and Mt. Whyte, fed by a mountain stream and a discharge stream from the glacier itself (plate IX, figure 2), which cascades over the lateral moraine from a dozen different places. The lakelet has an elevation of 6,554 feet, is largely filled with fine silt, and contains a number of low islands, supporting some vegetation. The outlet stream is marginal for about 500 feet and then enters the side of the glacier.

d. General drainage brook. The subglacial and englacial streams are all united into a single stream which emerges from the base of the ice at an elevation of 6,127 feet and back about 1,000 feet from the real nose, upon the west side. This stream cascades over the coarse blocks of the terminal moraine, receives a small tributary from Mt. Whyte, and rushes headlong to the lake, one mile distant, dropping some 450 feet. In comparatively recent time the discharge was through a tunnel which is being rapidly destroyed by melting. plate VIII, figure 4, shows the entrance to this tunnel as it appeared in 1904 and plate IX, figure 4, furnishes an interior view looking out and down the valley. At this time the opening was 12 feet high by 7 feet broad and the tunnel could be entered for a distance of 160 feet, when it appeared to have been clogged by ground-morainic material. The opening narrowed rapidly toward the inner end (plate IX, figure 3) and the severe melting of 1905 showed that it connected with an englacial passage leading towards the main moulin. This difference in the size indicates that when the ceiling of the portion of the tunnel shown in plate IX, figure 4, was being fluted by torrential waters, the bed of the stream was at a considerably higher level than that there shown and that the stream worked its way down from an englacial to a subglacial position. The amount of water discharged through this tunnel was probably no greater than that at the present time through the present exit. The floor of the tunnel, at its entrance in 1904, had an elevation of 6,192 feet, or 65 feet above the present place of discharge.

During periods of minimum melting, and always in the early morning, the amount of water discharged from the glacier is relatively small. Late in the afternoon and evening of a day of rapid melting it gushes forth with great power and volume (plate X, figure 1). It was impracticable to measure the amount of discharge at this exit, but measurements were made at the delta where the stream enters the lake. So little additional water was being received at the time from the adjacent mountain slopes that the results secured represented approximately the flow from the glacier itself. An accurate cross-section of the stream was secured by taking the level of the bed for each foot, establishing a gauge, and determining the velocity from surface floats. A calculation of the flow was made, after a week of minimum melting, by averaging the flow at 9:00 A.M. and at 6:00 P.M. During this period there were 0.671 inch of rainfall near the nose of the glacier. A similar determination was made after a week of maximum melting, with 0.030 inch of rainfall. These results gave 73 and 93 cubic feet per second for the average flow. At the time of the minimum flow the water at the exit from the glacier was found to possess 0.230 oz. of sediment to the cubic foot and 0.506 oz. during the time of maximum discharge. This is enough to make the water decidedly turbid. The total amount of sediment carried out daily during the maximum discharge period was estimated to be about six tons, and one-third this amount for the

FIG. 1.—Drainage from Victoria Glacier after a day of much melting.

FIG. 2.—Reference boulder A, Victoria Glacier, still embedded in the ice. Photographed July 30, 1898, by Prof. Charles E. Fay.

FIG. 3.—Stratified ice front, Victoria Glacier. Reference boulder A in the middle foreground, August 23, 1903; seventy-six feet from ice margin.

FIG. 4.—Front of Victoria Glacier, showing irregular stratification and shearing. July, 1904.

minimum period of flow. During the spring and fall the flow is very greatly reduced and must be very scant, or nothing, in the winter. Mr. Robert Campbell informs me that he has seen water in the stream, however, beneath the snow and ice of winter.

e. Water temperatures. The temperature of the water at the main exit was found to vary from 32.0° F. to 32.4,° at various times of the day. Near the site of the camp, just outside of the older of the two great block moraines, and some 2,000 feet from the exit, a series of observations was made upon the temperature of the water in the west branch of the drainage brook. The observations were made between July 2 and 27, 1904, and in the early morning, near midday, and in the evening, but not at any stated hours. Most of them were taken between 7 and 8 A.M.; 12 and 2 P.M., and 8 and 9 P.M. Of 56 observations, those for the morning averaged 35.4°, for midday 41.4°, and for the evening 35.2°. A small amount of drainage was received from Mt. Whyte, which must have materially affected the temperatures. Upon July 18, 1904, simultaneous observations were made at the glacier, camp, and at the delta, one mile below. The maximum temperature for the day was 51.7° F. and the minimum 34.8°. The results were as follows:

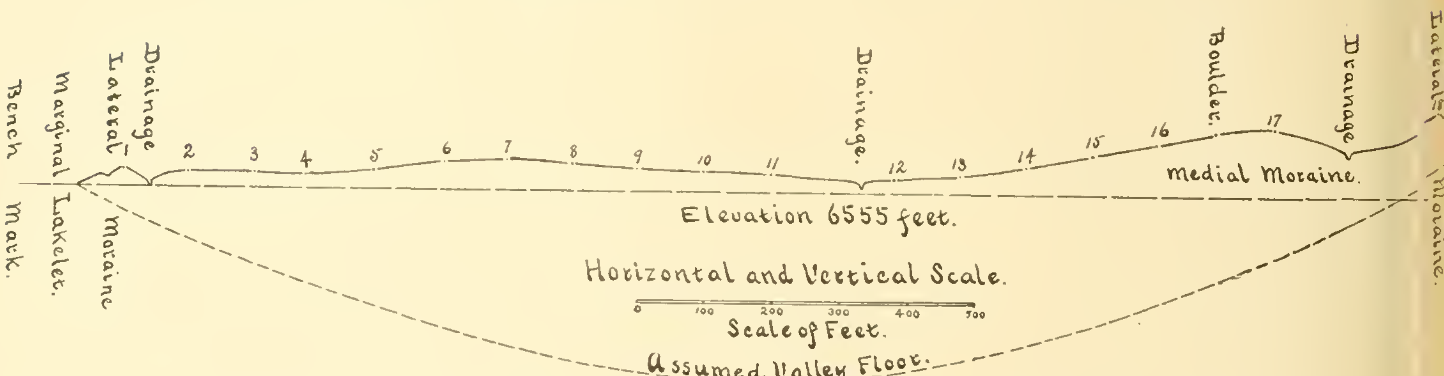
Time.	Glacier.	Camp.	Delta.
9:00 A.M.	32.4°	35.2°	35.8°
6:00 P.M.	32.4°	34.0°	36.0°

By the time the water has moved across Lake Louise to the foot, its temperature has been raised some 6° to 12°, the temperature ranging from 42° to 48°, during the summer months. The temperature of the Bow River at Laggan, into which Lake Louise is drained, was found to be 54.9° F., Aug. 15, 1904.

5. Forward Movement.

a. Measurements. Long before the attention of scientists was directed to glaciers as suitable subjects for investigation, the Swiss peasants had discovered that they possessed a forward, down-valley movement and that they slowly transported boulders and other objects left upon their surface. In 1841 the Bishop of Annency, M. Rendu, published his remarkable work, *Théorie des Glaciers de la Savoie* (edited by George Forbes, 1874, translated by Alfred Wills), in which he shows a surprising insight into the laws of glacial motion. "Between the Mer de Glace and a river," he writes, "there is a resemblance so complete that it is impossible to find in the latter a circumstance which does not exist in the former" (page 85). Since this was written, in 1839, glacial investigation has done much to justify, if not to actually verify the generalization. Streams of ice and streams of water have many characteristics in common, as well as important differences. All are agreed that the cause of the movement is, in both cases, the force of gravity, acting upon the mass itself, or some other mass in contact with it. As to the nature of the ice movement, those whose opinions should carry the greatest weight are not yet in agreement. So far as the present investigation is concerned the phenomena observed can be satisfactorily explained only upon the theory that under certain circumstances, and within certain limits, ice is capable of behaving as a plastic body, that is, capable of yielding continuously to stress, without rupture. In the discussion of this property of ice in the closing chapter of this report it is pointed out that the "plasticity" of ice, a crystalline substance, must be thought of as essentially different from that manifested by such amorphous substances as wax or asphaltum.

That the Victoria Glacier is flowing valleyward is capable of direct demonstration. From range lines across the glacier, the Messrs. Vaux marked the position of a certain large boulder July 26, 1899. This was on the portion of the glacier opposite the tributary and back some 6,800 feet from the nose. By July 24, 1900, this boulder was found to have moved forward 147 feet, while a second "near the terminal moraine" was found to have moved 115 feet.[1] So far as may be inferred from the phenomenon of the "dirt bands," to be later described, the former boulder was not in the locus of maximum surface movement, but some 360 feet to the west. In order to gather more definite data concerning the movement of the lower Victoria a line of 18 steel plates was set by means of a transit, the plates being placed as nearly as convenient at an average distance of



100 feet. The line of plates was back 3,600 feet from the nose of the glacier (see map) and was marked by setting the instrument over an established point upon a large block on the shoulder of Mt. Whyte and sighting across to the sharp edge of an easily recognizable cavity in the face of Mt. Aberdeen. The plates were of the style successfully used by the Vaux brothers upon the Illecillewaet Glacier and were $6 \times 6 \times \frac{1}{4}$ inches, with a 9-inch piece of $\frac{3}{4}$ inch gas pipe screwed into the center. They were given two coats of brilliant red paint, were numbered, and had the actual reference line marked in white, after the short piece of pipe had been driven into the ice. An arrow was marked upon each for purposes of orienting, in case they should become turned. In general, where the melting was greatest, it was found that the pipe did not sink into the ice and retain its vertical position, but allowed the plate to drop to one side. The end of

[1] *Proceedings of the Academy of Natural Sciences of Philadelphia*, Mch., 1901, p. 213. "Observations Made in 1900 on Glaciers in British Columbia."

the pipe, however, marked the spot upon the ice over which it had stood, so that its original position could be readily restored (see cross-section). It so happened that the next ten days in the valley were cool and cloudy, with small amounts of rain almost daily. This period was followed by ten days, and more, of bright warm weather, with considerable surface melting. After each of these periods the instrument was set in its former position and the original line again established, but upon ice which had moved down into this position. Measurements were made from this new line to the various plates and the amount of forward movement thus determined. The full data gathered from observations upon this set of plates are shown in table V. The relative vertical position of the plates is shown in the cross-section, as well as their relation to the surface features of the glacier.

TABLE V.

Observations upon the Series of Steel Plates, Set across the Victoria Glacier, July 9, 1904.

(Total Distance across Glacier along line of plates 2,167 feet.)

Station.	Distance from west side.	Elevation above sea-level, July 13, 1904.	Elevation above sea-level, Aug. 4, 1904.	Difference in level in 22 days.	Calculated daily ablation.	Motion for 10 cool days, July 9 to 19, 1904.	Motion for 10 warm days, July 20 to 29, 1904.	Average daily midsummer motion.	Motion for 423 days, July 9, 1904, to Sept. 5, 1905.	Average daily motion for 423 days.	Calculated motion for year.	Estimated thickness of ice.	Remarks.
	Feet.	Feet.	Feet.	Feet.	Inches.	Inches.	Inches.	Inches.	Feet.	Inches.	Feet.	Feet.	
1.	63.4	6585.60	6585.47	0.13	0.068	−0.787	1.181	0.020	0.21	0.006	0.18	62	Crest of left lateral moraine.
2.	163.2	6578.20	6576.11	2.09	1.116	0.394	0.000	0.197	3.00	0.084	2.56	100	Motion irregular.
3.	262.8	6577.74	6576.02	1.72	0.936	0.000	0.000	0.000	....	.....	.....	137	No summer motion. Plate lost in 1905.
4.	342.7	6575.26	6573.04	2.22	1.174	2.953	2.953	0.295	15.70	0.445	13.54	160	Motion for warm period retarded.
5.	443.3	6582.64	6579.89	2.75	1.386	7.874	10.630	0.925	26.10	0.744	22.63	200	Western slope of low crest.
6.	549.9	6595.27	6592.70	2.57	1.231	10.433	17.126	1.378	33.80	0.959	29.17	245	Western slope of low crest.
7.	642.1	6601.22	6599.24	1.98	0.866	11.811	22.835	1.732	47.60	1.350	41.06	275	Crest of low divide.
8.	741.4	6595.36	6593.06	2.30	1.009	12.402	27.362	1.988	56.50	1.603	48.76	292	Eastern slope of low crest.
9.	839.8	6589.06	6586.26	2.80	1.250	18.504	26.378	2.244	51.50	1.460	44.41	302	Eastern slope of low crest.
10.	938.3	6585.02	6582.15	2.87	1.292	18.110	25.984	2.205	72.10	2.045	62.20	306	Eastern slope of low crest.
11.	1037.6	6579.59	6576.65	2.94	1.273	19.882	33.661	2.677	76.30	2.165	65.85	306	Maximum motion for year.
12.	1222.0	6574.49	6570.86	3.63	1.724	18.701	22.638	2.067	74.20	2.105	64.03	287	Lowest plate.
13.	1320.5	6580.91	6577.11	3.80	1.735	18.701	36.024	2.736	74.80	2.122	64.54	276	Maximum summer ablation.
14.	1419.7	6593.45	6590.15	3.30	1.491	16.929	33.071	2.500	71.00	2.014	61.26	262	Gradual slope to medial.
15.	1519.1	6613.69	6611.45	2.24	0.959	10.827	31.693	2.126	67.40	1.912	58.16	252	Gradual slope to medial.
16.	1618.0	6629.03	6627.25	1.78	0.689	14.370	31.299	2.283	63.30	1.795	54.60	236	Gradual slope to medial.
Bldr.	1704.0	6647.90	6646.46	1.44	0.535	11.024	29.528	2.028	58.50	1.660	50.49	220	Boulder on medial moraine.
17.	1791.6	6653.14	6652.03	1.11	0.374	11.614	25.787	1.870	55.50	1.574	47.88	188	Crest of medial moraine.
18.	2083.5	6687.12	6687.15	−0.03	.....	−9.646	4.134	.....	0.17	0.005	0.15	80	Crest of right lateral moraine.

In column 7 is given the total forward movement for the cool period, July 9 to 19, from which the average daily movement can be seen at a glance by shifting the decimal point one place to the left. The greatest movement was shown by plate 11, almost 20 inches, and this was the plate nearest the centre. From this point the motion diminished very gradually toward the west, but less rapidly eastward, toward the crest of the medial moraine, and then fell off very suddenly. The plates in the crests of the two lateral moraines had moved up-stream, supposedly from the settling of the débris due to ice melting beneath. Plate 3 seemed to be located upon a stagnant portion of ice, showing no movement for either the cool or the warm period, and then could not be found in 1905, apparently because of the side cutting of a surface stream. For the warm period, July 20 to 29, the results are given in the next column for ready comparison. The motion is seen to be greater, almost twice as great for plate 14 and almost three times as great for plate 15. Both plates upon the lateral moraines had moved ahead, although that upon the right lateral had not yet regained its original position. Plate 2 showed no movement whatever for the warm period, and number 4 showed no increase of movement. In column 9 there is given the average daily motion for these 20 days of midsummer, which may be regarded as typical of the season. For this period the greatest forward movement was shown by plate 13, having a daily average of 2.736 inches. It is located some 287 feet east of the centre of the glacier, and, as previously pointed out, showed the maximum ablation. Number 3 showed no movement whatever. On September 5, 1905, the plates were again located, all being readily found except plate 3, and their distances from the original line determined. These results are listed in column 10, from which have been calculated the average daily motion and the motion for a year. In all cases there was a down-stream movement indicated, although very slight for the two lateral moraines. The greatest movement was shown by plate 11, the one nearest the centre of the glacier, amounting to a total of 76.3 feet for the entire period of 423 days, or a daily average of 2.165 inches. This represents a yearly motion of about 66 feet. The central position of the plate of maximum movement for the year was to be expected from the very straight course of this part of the glacier. Its daily motion for the year is about 81 per cent. of its midsummer motion, which means that for the greater part of the year the movement is fairly uniform. The table suggests that during the season of maximum motion there are cross-currents set up in the ice, and, with reference to the body of the ice itself, not the bed, even back currents. During the year, however, the impulse is steadily and regularly forward. Studies upon the dirt bands of Forbes, to be later discussed, indicate that as we approach the steeper ice slope opposite Lefroy, the motion is more rapid than that given in the table.

b. Frontal changes. The rate of melting about the nose and side of the glacier, in connection with the rate of forward movement of the ice, determines the behavior of the front. When these two factors are balanced the glacier appears to halt, and, if carrying débris, begins to build a terminal moraine. If either the rate of forward movement, or the rate of recession from melting, is in excess then the glacial extremity advances, or retreats, entirely regardless of the fact that the ice of the glacier is continually moving forward. Owing to the rock veneer which completely covers the nose of Victoria, the amount of melting even during midsummer is very small. The last episode here was one of advance, the glacier having extended itself, some decades ago, into a forest of spruce and fir and checked its own advance by mounting a heavy moraine of rock fragments which it was incapable of pushing aside (plate v, figure 1). The cut stumps and broken trunks which lie about the nose, some of them entirely out of reach of the present glacier, appear to have been produced by an avalanche from between Mt. Aberdeen and Castle Crags, which encircled the nose when it stood somewhat farther back than at present. Trees now growing in the path of this avalanche are 28.3 inches in circumference and by calculation should be 130 years old. In order to determine how the nose was behaving, three accurate measurements were made with a steel tape between definite points upon coarse blocks of the old moraine and upon others that seemed rather firmly embedded in the frontal slope. Between July 9 and September 13, 1904, in all 66 days, each of the latter blocks had settled back approximately an inch, presumably owing to the wastage of the ice beneath from melting. Confirmatory evidence that such melting was in progress was furnished by a small *clear* stream of water at 32°, which escaped through the rocks just west of the nose. Between September 13, 1904, and September 2, 1905, when measurements were again made, this small recession was partially made up, but the blocks still lacked .36 in. to .72 in. of regaining their former position. With the front so delicately poised it is evident that a very small additional impulse from behind would inaugurate an advance.

At a point 2,000 feet up from the real nose, at about the middle of the oblique ice front already noted, there lies a large red quartzite boulder, which was used by the Messrs. Vaux as a reference block. This is the largest of the three blocks in the middle foreground of plate x, figure 3, as it appeared in August, 1903. This boulder was observed protruding from the ice, a little over half-way up the face, in the midsummer of 1898, by Prof. Charles E. Fay. In this position it was photographed by him, and also a week later, when it had fallen. Plate x, figure 2, shows the boulder in position in the ice. In 1899, July 26, this boulder was found by the Messrs Vaux to be 20 feet from the ice front. How much of this 20 feet was due to recession and how much to the rolling or bounding of the block in falling, cannot now be determined. On July 24, 1900, the boulder was found to be 26 feet from the ice, indicating a recession of 6 feet for the year. August 23, 1903, the block was found by the writer to be 76 feet from the ice foot, giving an average recession since 1899 of 14 feet. The following July the block was marked with bright red paint, so that it could be readily located by others: "A. Ice foot 74.5 ft. 7/23/'04. Sr." The elevation of a line upon the face, determined by spirit level from Lake Louise as a base, was recorded as 6,264 feet[1] above sea-level. When compared with the distance noted above for the previous

[1] This elevation was based upon 5,675 feet for the height of Lake Louise above sea-level. The corrected elevation as now given by the Canadian Topographic Survey is 5,670 feet, or five feet lower.

year this would indicate an advance, whereas the glacier was actually in retreat. The necessity of taking the measurements as nearly as possible at the same corresponding time in the season becomes evident. In 1904 measurements were also made August 4 and September 13, giving distances of 76 and 86.45 feet respectively. If we assume a *uniform* recession between these last two dates we have a daily amount of 0.26 feet and for the interval between August 4 and August 23, at which date the measurement was made in 1903, an additional recession of 4.94 feet. This amount, added to that of August 4, gives 80.94 feet, and the approximate recession from August 23, 1903, to August 23, 1904, was 5 feet. In 1905 the measurements were made September 2, and gave a distance of 106.8 feet from the reference block to the ice foot. This means a recession of about 25 feet for the year 1904–5. For the series of six years 1899 to 1905 the total amount of recession observed at this point was 86.8 feet, or an average of 14.5 feet annually. The following summary for this boulder may be given:

1898.	Fell from ice early in August.
1899.	20 feet from ice foot.
1899–1900.	Ice receded 6 feet.
1900–1903.	Average recession of 19 feet.
1903–1904.	Ice receded 5 feet.
1904–1905.	Ice receded 25 feet.
1899 to 1905.	Average recession 14.5 feet.

About 375 feet nearer the nose a second block was selected for reference and upon July 23, 1904, marked "B. To ice 38.5 ft. 7/23/'04. Sr." Between this date and August 4, 1904, the recession amounted to 3.9 feet and up to September 13 equalled 11.5 feet. The distance from the block to the ice foot was again measured September 2, 1905, and amounted to 63.2 feet, indicating a recession between September 13, 1904, and the latter date of 24.7 feet. Calculated, as above, for the year September 2, 1904, to September 2, 1905, the recession was approximately 15 feet. Since the exposure of the ice face opposite blocks A and B is so nearly uniform, we may assume safely that the rate of melting upon the oblique face is substantially the same at the two points of reference. The diminished recession of the ice at B would then indicate that the forward movement of the layers here must be greater than at A. From data already cited it is seen that the forward movement at the nose is insignificant and it appears that the main current of ice, as it approaches the nose, is deflected to the westward and that the oblique ice wall is in reality part of the *front*.

c. Shearing. The steeply inclined ice front, having a slope of 46°, near reference block B, shows a succession of ice strata, more or less well defined, which dip back into the glacier at a rather steep angle. At the mouth of the abandoned drainage tunnel (plate VIII, figure 4, and plate XII, figure 3), these strata in 1904 had a dip of 26°, which is below the actual dip. Between these strata there is dust, sand, a little fine gravel, and, occasionally, a cobble-stone, but the amount of foreign matter is small and inconspicuous. A few consecutive days' visits to this part of the glacier, in early July, showed that a differential movement between adjacent strata seemed to be taking place (plate x, figure 4), the upper layers being pushed beyond the lower. There was not enough foreign matter in the layers to explain the phenomenon by differential melting. In the case of the South Point and other Greenland glaciers Prof. T. C. Chamberlin observed a jutting of the upper stratum which was apparently due to the more rapid melting of the under layer, owing to its heavier load of dark-colored débris and consequent more rapid absorption of the sun's heat. Upon the same glacier, however, he found very conclusive evidence that the upper stratum may be pushed bodily over the lower, giving rise to a shearing action between the adjacent strata.[1] In August, 1903, Prof. I. C. Russell found a similar phenomenon on one of the small glaciers visited on the Three Sisters, Oregon. In this case he thought the evidence conclusive that the jutting of the upper stratum was due to differential melting.[2] In order to ascertain whether or not this was a similar case of shearing, a place was selected 50 to 52 feet above the base of the ice and heavy spikes driven into the ice until their heads were flush with the surface. Three were placed in the base of the upper stratum, about three feet thick, and three corresponding ones in the upper part of the subjacent layer, which had a thickness of about two feet. July 21 the upper layer projected beyond the lower 19.7 inches at the place selected for observation. Two days later it was evident that the melting was greater upon the upper layer, in spite of which it now projected 24.4 inches beyond the lower. The spikes were now visited regularly for 10 days, July 25 to August 3, the amount of melting measured, as well as the amount of projection of the two layers, and the spikes reset. These measurements were necessarily rough, but they showed each day that the melting was greater upon the upper stratum, the average amount for each spike being 1.76 inches, while that for the lower stratum was 1.53 inches, or nearly $\frac{1}{4}$ inch less. Some sand and fine gravel, washed down from above, daily accumulated in the lee of the projecting upper layer and gave the appearance of a concentration of dirt in the upper part of the lower stratum. When this dirt was small in amount it was observed that melting was accelerated; when greater in amount, that the melting was retarded. The upper stratum continued to gain slowly, but irregularly; reached a maximum of 26.6 inches and closed at 25.6 inches, or about 6 inches more than at the beginning of the observations. The results are tabulated below for inspection. Time did not permit the verification of the results at other points where the same thing appeared to be taking place, but there seemed to be no question that the upper layer was moving bodily over the lower. This movement represents a shearing of the body of the glacier, the shearing-plane lying between the adjacent strata, but not a shearing of the ice itself. Knowing how readily iron absorbs heat it may be supposed that six-inch spikes might induce melting sufficiently to render their use unsatisfactory. Lying in the ice horizontally there was considerable melting about the outer half of the spike, allowing it to sag and slide

[1] *Journal of Geology*, vol. III, 1895, p. 676.

[2] "Glacier Cornices," *Journal of Geology*, vol. XI, 1903, p. 783.

forward, but they did not seem to penetrate the ice any by such action. But even if such an effect was produced to an appreciable extent, it would have been more pronounced upon the upper row of spikes, which received more sun's heat owing to their more exposed position, and the actual melting upon the upper layer would have been still greater than is indicated in the table. Although the purpose of the experiment was to ascertain the differential melting, rather

TABLE VI.

Shearing Observations, Victoria Ice Front.

Date.	Upper stratum.			Lower stratum.			Projection of upper layer beyond lower.	Temperature.		Remarks.
July 23	Melting about spikes.			Melting about spikes.				Max.	Min.	
July 25	2.75 in.	2.00 in.	2.50 in.	1.50 in.	2.25 in.	2.25 in.	25.2 in.	60.7°F.	35.0° F.	Cloudy.
" 26	2.00	2.06	2.25	1.25	2.25	2.25	25.0	55.2°	40.0°	Warm.
" 27	2.37	2.56	2.37	1.25	3.37	2.25	26.6	68.4°	38.8°	Warm and bright.
" 28	3.25	2.56	2.50	2.75	2.25	2.38	25.6	69.7°	45.4°	Very warm.
" 29	1.62	1.56	1.38	1.19	1.50	1.87	24.6	74.0°	45.5°	Cloudy.
" 30	0.87	0.69	1.25	0.94	0.75	1.06	25.0	74.0°	36.2°	Cool and cloudy.
" 31	1.75	1.19	1.00	1.00	1.06	1.44	26.4	50.4°	38.0°	Mostly cloudy.
August 1	1.50	1.63	2.00	1.63	1.38	1.50	26.2			Bright.
" 2	2.31	2.00	2.38	1.50	1.50	1.75	25.0			Bright.
" 3	2.00	2.12	1.50	1.38	1.62	1.56	25.6			Bright and warm.
10 days' obs.	Average melting 1.76 in.			Average melting 1.53 in.			Increase 5.9 in. since July 21.			

than the actual, it is interesting to compare the maximum average daily effect here observed with the maximum melting observed upon the surface of the glacier, where least protected by débris. See table v, column 6, plate 13, page 31.

d. Crevasses. The general forward movement of the ice, and its inability to adjust itself to inequalities in its bed, give rise to systems of cracks, or crevasses. These show that the limit of tensional strain, without rupture, has been exceeded in this part of the ice. They occur in all parts of the glacier from the bergschrund to the very nose, and when insecurely covered with snow, they form the greatest menace to glacial exploration. The inexperienced cannot be too strongly cautioned against the danger arising from these concealed traps, against which the judgment of best trained Swiss guides is sometimes pitted in vain. In passing from one portion of its bed to a sufficiently steeper slope, as that opposite the nose of Mt. Lefroy, v-shaped cracks in the ice occur, extending directly across the glacier. They penetrate to considerable depths into the ice, as measured in feet, but their depth, compared with the total thickness of the ice, is probably small, unless the change in the inclination of the bed is very abrupt, when they may reach the bed of the glacier. When these transverse crevasses have an east-west trend, the sun's rays strike the northern lip of the crevasse more strongly than the southern and, in the course of the season, it becomes more rounded. In passing down the slope the crevasse walls come together and the crevasse is healed, except for the slight depression caused by the greater melting upon the northern crevasse wall. It is into this depression, which becomes convex down-stream owing to the more rapid central movement, that fine débris may collect and give rise to the "dirt bands" of Forbes, to be presently described. As the glacier rounds Lefroy and enters a broader portion of its valley, it has a chance to spread laterally, and longtitudinal and somewhat radiating crevasses are opened which may intersect those having the transverse position. If the glacier is again contracted these crevasses will also be closed, and if any depression is left, it will slope down-stream and not have a tendency to collect débris.

The more rapid movement of the middle portion of the glacier, when compared with the sides, which are retarded by the friction of the valley walls, induces tensional strains between the central and marginal masses. In consequence, along the sides, there is opened up a characteristic system of marginal crevasses at right angles to the resultant strain. These extend inward and upward, making, theoretically, with the sides angles of about 45°. The difference between the central and marginal flow must reach a certain value, and be sufficiently abrupt, otherwise the ice seems capable of yielding without rupture. In this way we may account for the absence of marginal crevasses over the lower west side of the Victoria. The very sudden change in movement, shown in table v, between the margin and the ice of the near-by medial moraine, plates 18 and 17, is evidently responsible for the series of marginal crevasses that are seen between the line of plates and the tributary (see plate III). From their absence upon this side, farther down, we infer that the ice beneath the medial moraine becomes more sluggish as the main flow is deflected westward. Opposite Mt. Lefroy conditions are favorable for their formation and they are well represented upon either side. Opposite the tributary they do not occur, as the marginal ice is sufficiently yielding. Upon the tributary itself these crevasses are well represented, except over the collecting area for the Lefroy. After their formation their inner ends may be swung around until they assume a transverse, or even reversed, position, as seen upon the Aberdeen side of the Lefroy. Here we find one series, averaging N. 51° E. and making angles of about 66° with the margin but ranging from 52° to 86°; and a second series, many of them nearly closed, and apparently older than the preceding, having an average direction of N. 95° E. and making with the side angles of about 111°.

The size of many crevasses in the spring and their contents of fresh snow show that they may persist through a series of seasons. Sometimes they become partially filled with water which may melt out cavities in their walls and give rise to the most exquisite ice grottoes, a peep into which is worth miles of travel. The closing of crevasses sometimes confines pools of water, often under hydrostatic, or ice pressure, and as the surface of the ice is lowered by melting, the water suddenly bursts forth with geyser-like action. The compression of air enclosed in cavities, or brought in by surface streams, often gives rise to a bubbling at the surface and a faint hissing, or chirping sound—the "sighing" of the glacier.

CHAPTER III.

VICTORIA GLACIER (*Continued*).

1. Glacial Structure.

a. Stratification. In this chapter there is set off for description a number of features, especially well shown upon the Victoria and its tributary the Lefroy, but which were more or less well represented upon the other glaciers also and are characteristic of glaciers in general. Among the first of these is the stratification the origin of which in the névé has been given on page 22. It is conceivable that a stratification in the basal layers might arise exceptionally through the operation of differential stresses in the body of an unstratified glacier. As pointed out by Chamberlin in the case of the massive Greenland glaciers shearing-planes may thus arise leading to a concentration of débris. The lower stratum over which the shearing takes place may be protected from the shearing thrust, may be more heavily charged with débris, or may be more rigid because of its temperature and water content.[1] In the case of the Canadian glaciers studied it seems probable that the strata are depositional, in very large part, at least. Conditions most favorable for the formation of shearing-planes would seem to be found in the case of the Illecillewaet Glacier, owing to the body of ice and its rapid descent from its reservoir. The depositional stratification is almost completely obliterated by the ice cascade and none other has arisen to take its place.

The stratification of the Victoria continues throughout the glacier's extent, and is seen at the oblique front, in the drainage tunnels and channels, in the moulins, and upon the walls of the crevasses. The line of demarcation between adjacent strata is usually only a soiled streak, but sometimes there is sand, gravel, and an occasional cobble-stone. The strata vary in thickness from 12 inches to 10 or 12 feet, as seen upon the Lefroy. This thickness would indicate that 9 to 110 feet of loose snow had taken part in their formation. The average thickness of the Victoria strata is not too great to suppose that they may represent the accumulated and compacted snow fall of the year. Those of unusual thickness are to be ascribed to avalanches. About the mouth of the abandoned drainage tunnel in 1904 the stratification of the ice was well displayed (plate VIII, figure 4, and plate XII, figure 3) as previously referred to. Three strata here averaged 26 inches, the full thickness of the lower one not being seen. The uppermost layer was wedge-shaped and thickened from 13 inches to 81 inches. The strata all dipped back into the body of the glacier at an average angle of 26°, as measured upon the tunnel walls, but this was less than the actual angle when measured at right angles to the strike of the layers. The irregularities shown in the strata here, as well as in the oblique ice face, are probably due to the partial nourishment of the glacier by means of avalanches of snow and ice. Upon the regenerated Lefroy Glacier the strata are massive, 6 to 12 feet in thickness, having been produced entirely from the avalanches from Mt. Lefroy. These strata all dip towards the

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[1] See *Geology*, vol. 1, Chamberlin and Salisbury, p. 303.

FIG. 1.—Line of contact between two "dirt zones," Lefroy Glacier. These zones represent outcropping edges of depositional strata.

Aberdeen. Mitre.

FIG. 2.—"Dirt zones" upon Lefroy Glacier, frequently confused with "dirt bands" of Forbes. Compare figure 2, plate XVI.

region of accumulation, directly beneath the front of the hanging glacier. In the lower part of the glacier this dip averages 22°, ranging from 12° to 26°, while farther up-stream the dip is more gentle, only 5° to 10°, as well seen in the crevasse walls. The Mitre Glacier, near the junction of its two feeding streams, is crevassed and faulted and displays a very regular stratification (plate VII, figure 2).

b. Dirt zones. Upon a moderately steep slope, such as is found upon the lower Lefroy, the outcropping edges of the strata, somewhat differently charged with débris, give rise to broad contrasting zones which pass evenly and symmetrically around the slope. As generally seen these bands are convex in the direction of flow, but irregularities in the surface slope of the ice, or in the angles at which the strata come to the surface, may make them concave down-stream for portions, at least, of their course (plate XI, figure 2). The upper edge of one zone upon the Lefroy contrasts very strongly with the adjacent layer, as shown in plate IV, figure 2. It was the abnormal position of this line, first seen from the Devil's Thumb, that furnished the clue needed to decipher the relation of the Lefroy to the Mitre Glacier. A nearer view of this zone line, and two adjacent ones, is shown in plate VIII, figure 1, and a still nearer view in plate XI, figure 1. Because of the irregularity and small size of the strata, as well as the débris covering, the phenomenon is not well seen upon the Victoria. At the place where it should show the best it is, furthermore, obscured by the dirt bands of Forbes, with which the zones are often confused. These two features are so different in origin and significance, yet often so similar in appearance, that they should be sharply separated in the field and in descriptions of glaciers. Plate IV, figure 2 shows the dirt zones, upon the Lefroy, at the left, and the dirt bands, upon the Victoria, in the middle foreground.

c. Granular structure. A lump of ice from the body of a stratum, which has not yet begun to show any signs of melting, is compact, firm, brittle, without cleavage, and beautifully blue by transmitted light. It appears quite homogeneous, except for the presence of air spaces, which may be sparingly and irregularly scattered through the ice, or they may be arranged in seams, to be presently described. Under the polariscope, in thin slices, the ice is seen to be crystalline in structure and made up of closely pressed polyhedrons, ranging in size from hazel nuts to goose eggs. These polyhedrons are the so-called glacial granules, that may be traced back to the névé, growing smaller and smaller, upon an average, as we recede from the nose. They fit tightly together, interlocking perfectly, have curved rather than plane faces, and show no spaces nor signs of any cementing material between the individual granules. There seemed to be a correspondence between the size of the glacier and the size of the granules seen about the nose, the largest granules being observed in the Illecillewaet and Yoho glaciers, in the case of the latter ranging from 0.2 inch to 2.75 inches and averaging about one inch. From the fact that such granules occur in no other form of ice, that they may be traced back to the névé, becoming smaller and smaller and more numerous, the inference is reasonable that, in some way, these granules must be derived from those pellets which constitute the typical névé. The question as to how the granules are developed at once arises, but cannot be yet answered with certainty. (For a fuller discussion of this subject see page 127). That the larger are not produced by the simple freezing together of a certain number of the smaller pellets is shown by the fact that each mature granule is crystallographically homogeneous. Those who have written most recently upon the subject hold the view that the granules are permitted to grow by a process of partial melting and refreezing, the larger thus appropriating to themselves the water derived from the melting of the smaller. Mügge holds that this melting takes place at the outer limits of the individual granules because of the constant readjustment of pressures within the body of the glacier,[1] and in this change of the granules he sees the cause of glacial motion. Chamberlin believes that a similar change occurs because of differential stresses upon the granules undergoing constant adjustment, assisted by whatever heat energy may be conducted into the glacier from above.[2] Drygalski recently argues in favor of a melting of the granule by pressure both internally and at its outer surfaces, by which some granules may be completely liquified and subsequently refrozen.[3] Upon this action he bases his theory of glacial motion and the orientation of the granules about the nose, as brought out in his Greenland report in 1897 cited below.

Experiments of Hagenbach-Bischoff in 1883 showed that when two ice crystals, having differently directed axes, are pressed together they unite without melting into a single crystal, "the larger eating up the smaller." The union differs from the regelation of Tyndall in that there is a rearrangement of the molecules by which the resultant crystal is crystallographically and optically homogeneous. To distinguish it from the method of granular growth due to melting and refreezing it is spoken of as a "dry union." This principle applied to the glacier would lead to a continual reduction in the number of granules and a corresponding increase in their size, as pointed out by Hagenbach-Bischoff, Heim, and Emden. It will be shown later (page 128) that this theory of granular growth seems to the writer to best explain the remarkably perfect preservation of the often delicate laminæ and blue bands seen about the nose and sides of the glacier. Combined with the special type of plasticity exhibited by ice crystals this method of perfect dry welding may explain the absence of noticeable distortion of the ice granules, which, as urged by Chamberlin, should be observed in the direction of flow if the glacier moves because of its viscosity.

In order to determine whether or not there was any tendency towards the orientation of the granules in the basal layers about the nose, thin slabs of ice

[1] "Weitere Versuche über die Translationsfähigkeit des Eises, nebst Bemerkungen über die Bedeutung der Structur des gronländischen Inlandeises," *Neues Jahrbuch für Min., Geol., und Pal.*, 1900, Bd. II, S. 87 zu 98.

[2] "Recent Glacial Studies in Greenland," Presidential Address before the Geological Society of America, *Bull. Geol. Soc.*, vol. 6, 1895, p. 211; "A Contribution to the Theory of Glacial Motion," Decennial Publications of the University of Chicago, vol. IX, 1904, pp. 10 and 11; *Geology*, by Chamberlin and Salisbury vol. I, 1904, pp. 299 to 306.

[3] "Ueber die Structur des grönländischen Inlandeises und ihre Bedeutung für die Theorie der Gletscherbewegung," *Neues Jahrbuch für Min., Geol., und Pal.*, 1900, Bd. I., S. 71 zu 86.

Fig. 1.—Glacier capillaries, Yoho Glacier, outlining glacial granules. Much reduced in size.

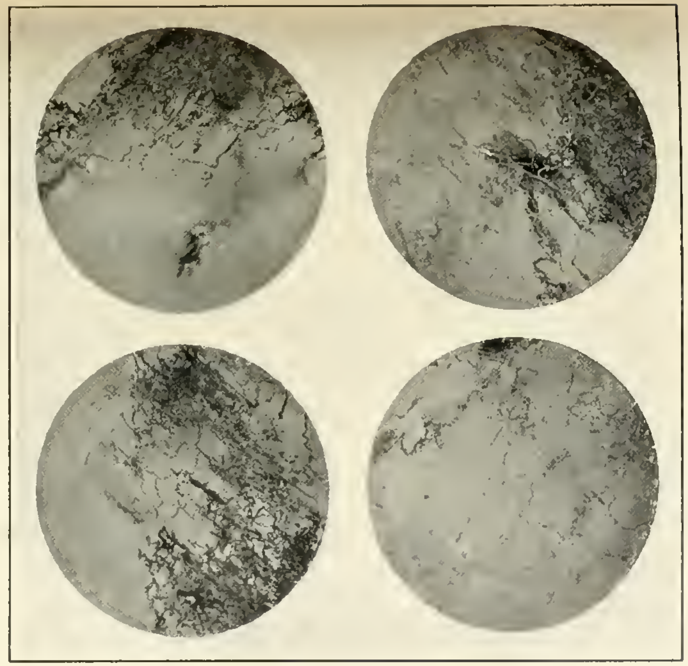


Fig. 2.—Glacier capillaries, infiltrated, Illecillewaet Glacier. Much reduced in size.

Fig. 3.—Stratification upon wall of ice tunnel, Victoria Glacier, July, 1904. Steel tape run out to 50 cm. Observe glacial granules and blue bands and note unconformity of latter with strata.

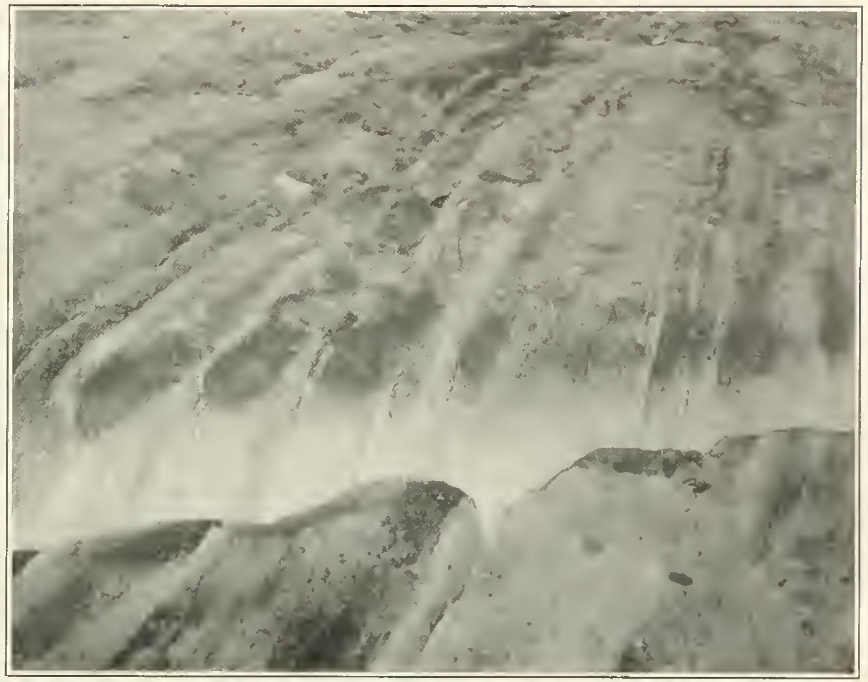


Fig. 4.—Blue bands seen in upper part of Lefroy Glacier, cutting strata at high angle. A perfect example of a regenerated glacier.

were sawed out in various directions and melted down to thin slices by rubbing them over the face of a warm saw-blade. Examining these sections with the polariscope, it was found that in the case of those cut horizontally from the glacier, from $\frac{1}{4}$ to $\frac{1}{3}$ of the granules remained dark when revolved. In the case of sections cut vertically, either across or lengthwise of the glacier, only an occasional granule was found to show this phenomenon. From this it appears that there is a tendency towards the orientation of the granules near the lower portions of the Victoria, Yoho, and Illecillewaet glaciers, a considerable percentage of the granules having their main optic axes in a vertical position. The same phenomenon was observed by Drygalski in the case of the Greenland glaciers.[1]

d. Capillary structure. When glacial ice is subjected to a moderate melting temperature for a sufficient length of time there is developed a network of capillary tubes, at the junctions of three or more granules. These tubes are approximately circular in cross-section and from 0.008 inch to 0.04 inch in diameter. Their walls reflect the light strongly and give the appearance of silver threads, more or less perfectly outlining the granules. From the ease with which liquids course through the tubes one infers that they are free from or contain but little air. From beneath the margin of the Yoho Glacier it was possible to get some of them upon the camera-plate, although, many of them being out of focus, they all appear disconnected (plate XII, figure 1). By making a strong solution of potassium permanganate and placing it in a basin hollowed in the ice, the capillaries were in a few minutes beautifully infiltrated, the red solution contrasting strongly with the rich blue ice (plate XII, figure 2). Upon the faces of crevasse walls, and in the drainage tunnels, where the sides are smoothed by melting, these tubes may be seen in longitudinal section, forming a pattern by which the irregular granules are outlined. These are the tubes which Agassiz and Forbes found in the Alpine glaciers, but which Huxley and Tyndall did not discover. Agassiz was in error in supposing the entire body of the glacier to be permeated with such a system of capillary tubes and Huxley in denying that any part of it was.

e. Melting features. As melting proceeds the capillaries become larger; irregular, "crinkly" spaces are opened between the faces of adjoining granules, and the delicate network is gradually obliterated, as shown in portions of plate XII, figure 2. With this increased reflecting surface the ice loses its deep blue color, becomes whiter, and when the granules are small it assumes somewhat the appearance of névé. A slight pressure now, or a sharp blow, will cause the ice to crumble into its component granules. These granules are shown, but rather indistinctly, in plate XII, figure 3. While still in position, as well as after they have fallen apart, the granules are seen to be covered completely with delicate parallel ridges and rows of fine points winding over the surface and having no definite direction with reference to the crystal. The ridges and rows of points are about 0.04 inch distant, but show some variation, and form a complicated pattern that is different for each granule, suggesting more strongly than anything else the ridges seen upon the inside of one's finger-tips. This phenomenon

[1] *Grönland-Expedition der Gesellschaft für Erdkunde zu Berlin, 1891–93*, Bd. 1, 1897, S. 494.

was noted by Drygalski in the granules of the Greenland glaciers and described briefly upon page 488 of his report cited. It had been previously observed and described by Emden in his paper *Über das Gletscherkorn*, p. 22, figure 5, and designated as melting water curves. While neighboring granules were in position, no correspondence could be made out between the ridges and furrows of adjoining faces. An attempt was made to take impressions of the markings but no suitable material was at hand. The wall preparation "alabastine" reproduced perfectly the finger markings, but refused to work with a wet ice surface. The "stripes of Forel" are delicate ridges, passing around the granules at right angles to the main optic axis, and evidently connected with the intimate crystalline structure of the crystal. They mark the edges of the very fine plates of which each ice crystal is composed, placed together with their flat faces perpendicular to the main optic axis. The ridges here described are entirely different and do not suggest to the writer any possible explanation. They are certainly due to the manner of surface melting but it is far from apparent what could give rise to such a pattern. In the prisms of lake ice Emden found both the melting curves and Forel's striping present, with an intermediate type of ribbing, and concluded that all three were due to one and the same cause and independent of the structure of the crystal (p. 24).

Granules that have been well acted upon by the sun show a system of very flat, circular disks, all with their planes parallel and at right angles to the main optic axis. These were first observed and figured by Agassiz in his *Système Glaciaire*, 1847 (plate VI, figures 7 and 10) and described also in his *Geological Sketches*, vol. 1, p. 275. They were believed by him to be air bubbles, flattened by pressure, although observed to lie differently in adjoining granules. These are now known as "Tyndall's melting figures," described in his *Glaciers of the Alps*, Ed. 1896, pp. 353 to 361. They represent "vacuous space," left in the ice by the contraction of the water when changed from its solid to its liquid condition, the melting planes coinciding with the crystalline plates, of which the granule appears to be composed. They are thus serviceable in enabling one to determine the direction of the main axis of each granule, but there were not enough of them seen at one time about the nose of the glaciers to settle the question of the orientation of the granules.

f. Blue bands. Many observations were made upon the blue bands, of which the strata are generally composed, with the hope of shedding some light upon their position and direction in the ice and their relations to the strata. In general, they were found well developed about the nose and along the sides of the glaciers, well up toward the névé region. The lower Victoria has too much débris covering to enable them to be well seen at the surface, but in the tunnels and moulins and along the walls of the surface streams they are to be seen in a good state of development. At the mouth of the tunnel they were found to average 0.59 inch to 0.75 inch and to dip back into the glacier at an average angle of 9°, while the average slope of the strata was 26°. This unconformity of the laminæ and strata is well shown in plate XII, figure 3, although the laminæ become indistinct in proportion as the granules separate. In the moulins, opposite the oblique ice face the average inclination up-stream was found to be 30°. Under the medial moraine, near the nose of Mt. Lefroy, the bands were longitudinal, vertical near the centre but radiating, fan-like, upon either side; the outer ones inclining as much as 45°. Although for over 65 years the subject of study, we are not much nearer an explanation of this common glacial feature than when first observed in 1814 by Brewster. The idea of Forbes that they represent ice-filled crevasses, or shearing-planes, has been generally abandoned. The early view of Agassiz, that they represent the original lamination of the névé snow, successively compacted by rain or melting, and then frozen (*Geological Sketches*, p. 247), has been revived by Reid[1] and Hess.[2] Crammer accepts this same view of the origin of these bands, and argues further that they represent shearing-planes along which the motion of the glacier proceeds.[3] In his prize essay, *Über das Gletscherkorn*, p. 37, Emden advances the theory that these blue bands were formed by the overflow from glacial brooks, infiltrated and frozen. The view of Tyndall, that these blue bands result from pressure and, when formed, are at right angles to it, had received very general acceptance. In the former view the lamination is to be regarded as an organic part of the glacier; in the latter, the banding is of secondary origin, and might not be present at all, under certain circumstances. Tyndall's theory is set forth clearly in his *Glaciers of the Alps*, chapter 31, and is summarized thus: "The ice of the glacier must undoubtedly be liquified to some extent by the tremendous pressure to which it is here subjected. Surfaces of discontinuity will in all probability be formed, which facilitate the escape of the imprisoned air. The small quantity of water produced will be partly imbibed by the adjacent porous ice, and will be refrozen when relieved from the pressure. This action, associated with that ascribed to pressure in the last section, appears to me to furnish a complete physical explanation of the laminated structure of glacier-ice."

The Lefroy Glacier, being a regenerated and at the same time a parasitic one, moving in a different direction from its host, furnishes an opportunity for testing our two theories. In plunging 2,000 feet into the valley all traces of the original stratification and lamination of the névé must be destroyed. Since the avalanches of snow and ice occur only, or mainly, during a few months of the year, it may be safely granted that layers of this material will be spread out, more or less unevenly, about the base of the cliff, alternating probably with layers of snow which falls directly into the valley, or is in part drifted there. The result of this action will be to restore the stratification seen in the hanging glacier at the crest of the precipice. It cannot be assumed, however, that anything like the original lamination of the ice can be reproduced. Possibly around the margin of the area covered by the avalanches, there might be built up a succession of

[1] "The Relation of the Blue Veins of Glaciers to the Stratification," *Comptes Rendus IX. Congrès Geol. Internat. de Vienne*, 1903, pp. 703 to 706.

[2] *Die Gletscher*, 1904, p. 175.

[3] *Eis- und Gletscherstudien. Neues Jahrbuch für Min., Geol., und Pal.*, XVIII. *Beilage-Band*, 1904. pp. 105 and 106.

fine layers, but such a deposit would be of limited thickness since it would very soon be pushed outward and beyond the reach of the snow dust. The bulk of the avalanched ice would come down in great heaps, which could show neither original nor acquired lamination. Granting that some of the avalanched snow and ice would become finely stratified, we would expect it to alternate with much more that was not, and with frequent layers, produced by the direct snowfall into the valley, showing the typical névé lamination. Furthermore, the position of the Lefroy upon the Mitre is such that these laminæ along the sides of the former, as well as over the surface, should run across the valley and should be entirely conformable with the strata.

Upon the other hand if the banding is of secondary origin and the result of pressure against the valley walls, it should be entirely similar in adjacent strata of the same character, exactly as found in ordinary glaciers not formed as is the Lefroy, should be found near the sides of the valley and parallel with them, and should show an utter disregard for the position of the Lefroy strata. In ascending the Lefroy to apply our test we find a beautifully perfect and typical banding upon the Aberdeen side, well shown upon the crevasse walls, under the lateral moraine. The inclination of the blue bands is very steep, ranging from 72° to 90° and averaging 83°, as they dip downwards and into the body of the glacier. These bands are continuous across the gently inclined strata and cut them at a high angle. Plate XII, figure 4, shows the perfectly developed bands, the margin of the glacier lying to the right, but does not give the desired view of the strata. Toward the centre of the Lefroy these bands become obscure at the surface, or disappear entirely, but are found again upon the Lefroy side, between the collecting region and the nose of Mt. Lefroy. So far as this feature is concerned the Mitre and Lefroy seem to be a unit and the evidence is all in favor of the pressure theory.

Near the nose of the Illecillewaet Glacier the blue band structure is very perfectly shown about the sides, as seen in plate XIII, figure 1. There is no lateral pressure upon either side and the bands conform with the valley floor. Furthermore, they would be conformable with the strata, providing the latter were present, but these have been destroyed, presumably at the ice cascade farther up the slope. It may be maintained that at such a cascade it is only the superficial layers that are disrupted and that their fragments are destroyed by melting, while the basal layers are preserved intact. This is undoubtedly true, at times, but in the case of the Illecillewaet, the stratification, well seen above the cascade, has been destroyed to the very base and it is difficult to believe that the much more delicate lamination could possibly have escaped destruction at the same time. Beneath this same glacier boulders are seen fluting the under surface, as the ice is pressed against them and melted; this is shown in figures 1 and 2, plate XXXIV. If the banding were simply the original névé stratification the edges would be cut off squarely. Upon examining the ice which has been pressed against a boulder there may be seen a set of bands curving about the stone, as though they had been there produced.

Blue bands giving rise to "dirt stripes," near nose of Illecillewaet Glacier. Bands would here be conformable with strata if latter were present.

FIG. 2.—Contorted blue bands, Yoho Glacier. Supposed to indicate differential ice flowage.

. 3.—Ice dyke filled with two tiers of horizontal ice prisms meeting towards center.

FIG. 4.—Crevasse in Victoria Glacier, showing how superficial débris may attain an englacial or subglacial position.

Wherever observed, the phenomenon of blue bands suggested the structure in rocks known as *schistosity*, rather than *stratification*, the bands thinning out and overlapping. It is possible that they may still be due to pressure and yet the ice may not have become liquid, as Tyndall supposed in order to account for the scarcity of air bubbles in the blue bands, when compared with the whitish vesicular ice in which they are embedded. There may be serious doubts as to whether the pressure has been sufficient to produce liquefaction in all such cases where the bands occur, and there is no reason for thinking that the crystalline condition of the ice would be essentially different in refreezing. We may account for the irregular and often contorted banding (plate XIII, figure 2) by assuming that differential movements have occurred in the ice mass since the bands were formed. A double set might be induced without the complete obliteration of the first. It is quite possible that, in the case of a glacier of the simplest supposable type, having a very even bed and without the restraint of rocky walls or lateral moraines, the original lamination of the névé would be preserved to the nose and give rise to a certain type of "blue band." It would seem that such a type, however, could be distinguished from the more common variety and that it would lose in distinctness towards the nose. The writer had come to the conclusion that the diverse views held by investigators concerning the origin of these bands were due to the fact that two very similar structures had been studied under the same name, when his attention was attracted to the following paragraphs written by Agassiz when glacial study was still in its infancy:

"Undoubtedly, in both these instances, we have two kinds of blue bands, namely: those formed primitively in a horizontal position, indicating seams of stratification, and those which have arisen subsequently in connection with the movement of the whole mass. . . . With these facts before us, it seems to me plain that the primitive blue bands arise with the stratification of the snow in the very first formation of the glacier, while the secondary blue bands are formed subsequently, in consequence of the onward progress of the glacier and the pressure to which it is subjected. The secondary blue bands intersect the planes of stratification at every possible angle, and may therefore seem identical with the stratification in some places, while in others they cut it at right angles." *Geological Sketches*, vol. I, pp. 260 and 261.

In this report the writer uses the term *laminæ* by which to refer to these "primitive blue bands" arising in the névé, and *blue bands* for the similar, but essentially different, structure resulting, apparently, from pressure, or from some other possible agency.

g. Ice dykes. These were well developed upon the lower Lefroy in the early part of the summer, but became somewhat obscured as the season advanced. They were found sparingly upon the Wenkchemna, but were not observed upon the other glaciers studied. They consisted of gashes in the body of the ice, apparently former crevasses, from two to fifteen inches across, which were filled with columnar ice crystals. The columns varied in diameter from $\frac{1}{4}$ to 1 inch and stood at right angles to the crevasse walls, having thus an approximately horizontal position. Very commonly the inner ends of the columns met and interlocked at the centre, but sometimes they were simply attached by their bases to the crevasse walls and left a space at the centre. Plate XIII, figure 3, will give some idea of the appearance of these dykes, although the individual ice crystals could not be made to show in a general view. As a rule the columns were straight, but sometimes curved and geniculated. The dykes were sometimes many feet in length, occasionally cutting across the walls of crevasses, presumably younger in age. In certain cases similar columns were found filling elliptical cavities in the ice, the crystals meeting at the centre. Such structures as these were observed by Agassiz upon the Aar Glacier and described by him in 1847 under the name of "*glace d'eau.*" [1] Although their origin was not understood he clearly saw that they resulted from the freezing of water in cavities in the ice. The ellipsoidal cavities with their radially arranged columns were figured upon plate VI of his atlas and described under the name "*étoile de glacier,*" or "*Gletscherstern*" (p. 187). These structures probably arise from the freezing of water-filled crevasses, moulins, and smaller cavities, the cooling surfaces being the walls of the cavity, instead of the atmosphere. When a lake surface freezes similar columns of ice are formed, with their main axes at right angles to the cooling surface, and, hence, ordinarily vertical. In the case of these dykes the columns also take a position at right angles to the surface of refrigeration, but these surfaces now being vertical the columns assume a horizontal position.[2] If the freezing is complete, the columns meet at the centre, the growth of the columns proceeding at about the same rate, inward from the sides. Should the water be drained off before the freezing is complete a space will be left at the centre. They are probably formed in the early part of the season, while the body of the glacier still retains some of its winter's temperature and after the melting has proceeded far enough to supply the necessary water. After being once formed they would persist through many seasons, although their upper surfaces might be obscured by various agencies. Somewhat similar dykes were sparingly observed upon the western side of the Lefroy but filled with granular ice, instead of the ice columns. Obviously these have had an entirely different history. The most plausible explanation is that they represent crevasses which were filled with the granular ice avalanched from the hanging glacier upon Mt. Lefroy.

2. Surface Features.

a. Superficial débris. The narrow valley through which flows the upper third of the Victoria Glacier, permits the avalanches of snow and ice to distribute rock débris over the entire surface. The most of this material is derived from the Mt. Victoria side, from which the avalanches may shoot completely across

[1] *Nouvelles Études et Expériences sur les Glaciers Actuels,* 1847, Première Partie, p. 185, plate VI, figures 14, 15, et 16.

[2] While this report is going through the press the author has been enabled to study the valuable paper of Crammer referred to upon page 43. Under the head of *Leisten* he describes similar structures (p. 104) and ascribes to them the origin here given.

FIG. 1.—Stony till, left lateral moraine, Victoria Glacier. Manufactured beneath hanging glacier upon Mt. Victoria and carried down with avalanches.

Whyte. Devil's Thumb. Bow Valley. Lake Louise.

FIG. 2.—Sharply crested left lateral moraine, Victoria Glacier. Moraine consists of a core of ice over which is spread a relatively thin covering of clay, sand, and rock fragments.

the valley. This being the region of accumulation, rather than melting, the rock débris is almost completely enveloped in snow and remains temporarily covered (plate v, figure 2). As the névé is pushed beyond the snow-line upon the glacier, surface melting begins and the rock fragments begin to make their appearance at the surface. As this action continues the rock rubbish is concentrated more and more, forming an almost complete veneering over the lower third of the glacier, completely obscuring the ice except where it has been incised by the drainage streams. The most of this material is sharp and angular, consisting of irregular fragments of quartzite, sandstone, limestone, dolomite, and quartz and argillaceous schists; in the main of Cambrian age. The ice lying immediately to the west of the medial moraine has come from the Lefroy side of the valley and being less well covered with débris has experienced more surface melting. This depression thus formed, shown in the cross-section along the line of plates (page 30), determined the position of the main drainage stream, previously described. The effect of this débris, in general, is to retard surface ablation and recession about the nose, so that the glacier attains a lower altitude than would otherwise be possible for it under the present climatic conditions. So far as we may judge from the ice front, the walls of the tunnels, crevasses, moulins, and drainage streams, the Victoria is not carrying much englacial material. A portion of this is in the position originally deposited in the névé and a portion has worked down from the surface by means of the crevasses, as shown in plate XIII, figure 4.

b. Lateral moraines. Along the margins of the upper Victoria and Lefroy conditions are especially favorable for the reception of rock detritus, both from the action of the ice avalanches and from the various weathering agencies that are operating upon the overtowering cliffs. Material derived from the cliff walls will ordinarily be sharp and angular, but may rarely show a single glaciated face, produced when in its original position during an earlier stage of glaciation. Most of this has been pried loose by the water in the seams and joints expanding in the process of freezing. The material carried by the hanging glaciers is almost, if not entirely, subglacial and has been subjected to severe abrading action between the ice and its rocky bed. Boulders, cobbles, and pebbles have had their corners and edges partially rounded, have had their faces bruised, gouged, and irregularly scratched, and are embedded in glacial sand and clay, of a bluish gray color. This ground-morainic material, mixed indiscriminately with that from the cliffs, is heaped up along the névé margins, embedded in snow and ice. Moved slowly along, very slowly compared with the central portions of the névé, the quantity is augmented and by the time the snow-line is reached there is formed a thick band of this débris covering the margin of the ice. Protected from the action of sun and rain more effectually than the general surface of the glacier, in spite of its débris covering, the ice beneath melts less rapidly and the marginal material is gradually elevated, with reference to the general surface. About the sides of this marginal ice ridge the débris slides and rolls down, allowing the less well protected ice above to melt into a sharp crested ice ridge, with a veneering of rock rubbish, the whole looking like a great railroad embankment, as seen in plate XIV, figure 2. The ordinary visitor is scarcely prepared to admit the existence of the ice core, which constitutes, in reality, the main bulk of the ridge (see plate XL, figure 1, from the Asulkan Glacier). In this way are formed the lateral moraines. Should the glacier completely disappear from the valley by melting it is obvious that the lateral moraine would be gently set down along the side of the valley, forming a ridge, but of insignificant proportions compared with its apparent bulk upon the glacier.

Upon the western margin of the Victoria, the glacier's left, opposite the entrance of the tributary, there occurs a considerable mass of angular débris, contributed from the Mt. Victoria side of the valley. Most of it is arranged in three or four somewhat poorly defined ridges, parallel with the margin of the glacier. A sudden contraction occurs here in the breadth of the glacier (see plate III), and there is continued a prominent, sharp-crested ridge for one-quarter mile, marking the margin of the glacier and losing gradually in height (plate XIV, figure 2). This portion of the left lateral consists almost entirely of ground-morainic material derived from the hanging glacier upon Mt. Victoria (plate XIV, figure 1). Soaked with water after heavy rains, mud flows occur, upon the surface of which cobbles and small boulders are slowly moved down the marginal slopes, thus reducing the covering of the ice core and permitting further melting. Along the base of Mt. Whyte there are found two small moranic ridges, consisting mostly of angular material, from which the ice has withdrawn rather recently. They appear to be the continuation of the two outer ridges which farther up-stream rest upon the ice itself.

The right lateral of the lower Victoria is derived entirely from the right lateral of the double tributary, already described. It consists at first of two high, very sharply crested ridges, mainly of ground moraine, which can be traced around into the great accumulation dumped at the base of Mt. Aberdeen by the parasitic Lefroy Glacier (plate VIII, figure 1; plate XV, figure 1). The angular material has been derived mainly from Mt. Aberdeen, while the ground moraine comes from the hanging glacier of Lefroy, as previously described. The inner of the two morainic ridges is being destroyed by sliding and mud flows into the depression between it and the near-by medial moraine. In places it has become so sharp that only with the greatest difficulty can one maintain a foothold upon its crest. About 2,000 feet back from the nose, an outer third ridge makes its appearance (plate XV, figure 2), and together the three pass around and over the nose, separating into minor ridges and mingling with those of the medial and frontal moraines (plate IV, figure 1). The lower portion of this moraine has the appearance of composure and comparative stability, giving support to moss, ferns, alpine plants, shrubs, and evergreens. One Lyall's larch was noted 8 feet high and 2 inches in diameter at the base.

Since the upper Victoria receives relatively little material from Lefroy, the right lateral above the tributary is rather meagre, and inconspicuous. As

FIG. 1.—Ground-morainic material manufactured beneath hanging glacier upon Mt. Lefroy and carried across Mitre Glacier by parasitic Lefroy Glacier. Beginning of ridges seen below in figure 2.

FIG. 2.—Right lateral and medial moraines of Victoria Glacier. Longitudinal ridges in lateral are well shown, the work of the parasitic Lefroy Glacier.

previously pointed out, a small amount of ground moraine escapes from being carried across the valley and moves down in the left lateral of Lefroy. In addition to this there is a large detrital cone, with its base resting upon the ice, and slowly dealing out morainic material as the ice moves down the valley (plate IV, figure 2). The covering of the general surface of the lower Victoria with rock débris prevents a great amount of differential melting, so that the lateral and medial moraines attain no great height.

c. Medial moraine. Owing to the stream-like nature of the flow, the left lateral of the Lefroy and the right lateral of the upper Victoria unite at the nose of Mt. Lefroy into a single medial moraine. This is at first a poorly defined ridge, but it becomes higher and broader as it moves across the valley from which emerges the tributary and serves as a divide for the two main drainage systems (plate IV, figure 1). Owing to the small volume of ice delivered to the Victoria by the double tributary, the medial moraine lies close to the right lateral, being separated at first by a deep depression, shown in plate XV, figure 2, which gradually disappears below as the two moraines merge. The western slope of the medial becomes long and gradual in the lower part. The entire length of the moraine is about 7,500 feet. Toward the nose it broadens as shown upon the map and in plate IV, figure 1 and becomes poorly defined, implying a sluggish condition of the ice upon which it rests. Its crevassed condition in the neighborhood of the line of plates was described upon page 37. Owing to the source of the material above noted the moraine contains a certain amount of ground-morainic material, but the bulk of it is angular and consists of quartzites, sandstone, schists, dolomite, and limestone. Some of the blocks show algæ, tracks, lingulas, and bryozoan-like stems. It has practically all been derived from Mt. Lefroy.

d. Terminal moraine. Although the front of the ice at the nose is in a condition of halt, the ice is practically stagnant and no frontal moraine has yet been formed (plate V, figure 1). Along the oblique ice front the retreat has been gradual enough to distribute the superficial and englacial rock débris somewhat uniformly over the valley floor and there has thus been formed no prominent ridge, as shown in plate VIII, figure 4. The apparent heaps seen at the right, alongside the face, still contain a core of ice, which will eventually melt and allow the rock to settle upon the valley floor. A small ridge, from 100 to 125 feet back from the ice, indicates a somewhat recent short period of halt, perhaps but one or two decades ago. It is quite probable that this halt was contemporaneous with that of the Illecillewaet, which closed in 1887. Between the oblique front and the nose conditions have been favorable for the formation of a somewhat poorly defined terminal moraine, *i. e.*, the front has been in a condition of halt while the ice was moving forward and dumping its load of angular débris. Two of the ridges that pass across the glacier, just back from the nose, extend off the ice upon the terminal moraine, without interruption, testifying still further to the sluggish condition of the ice about the nose. The medial moraine has introduced some ground-morainic material into the mass which has furnished a foothold for vegetation. Spruce and larch are climbing up the slope, the largest of the former showing

70 rings of growth and of the latter 77 rings. It is over this morainic heap that the drainage brook from the glacier cascades. The swift stream and its load of hard angular sediment have a perceptible rounding effect upon the corners, edges, and faces of even the hardest quartzites. This effect was most strikingly shown in quartzite boulders lying in the bed of a glacial stream coming from the Asulkan ridge.

c. Dirt bands. Under this term there was described by Forbes, in 1843, (*Travels through the Alps of Savoy*, p. 162), a superficial feature of certain glaciers which is of much interest and, possibly, of much importance. It is found in those glaciers which change their slope sufficiently to give rise to a distinct system of transverse crevasses, not necessarily to a cascade or ice-fall. The phenomenon was not understood by Forbes himself and, by various writers since,[1] has been confused with the *dirt zones*, described upon page 39, which are the outcropping edges of variously marked strata. It is to the keen observation and shrewd interpretation of Tyndall that we are indebted for the true explanation[2] of the feature. The Victoria and the Lefroy glaciers furnish an excellent opportunity for the study of dirt bands under very simple conditions, as well as the dirt zones for comparison. The two types of structure may be gotten upon the same photographic plate and are well shown in plate IV, figure 2. In very simple form the dirt bands may be seen cutting across the dirt zones upon the lower Lefroy, owing to the abnormal position of the latter. Under ordinary conditions the two would be more or less conformable and possibly difficult to separate.

The typical dirt bands are of such a nature that they can be seen most strikingly at a distance of a half-mile or more from the glacier and at a considerable elevation above it. When once seen, however, it is possible to locate them in a very general way while upon the surface of the glacier itself. In the summer of 1904, from the summit of the Devil's Thumb, which overlooks the Victoria Glacier from a height of 8,000 feet, there could be counted 23 soiled streaks passing across the glacier. Beginning near the crest of the ice slope opposite the nose of Mt. Lefroy, the bands were narrow, straight, and extended nearly across the glacier. They showed so dimly that there was uncertainty in regard to the count, until they had been gone over a number of times. Upon the face of the slope they became more distinct, curved so as to be convex down-stream, and correspondingly shortened. A few of them could be traced around into the transverse crevasses which had not been completely closed. Beyond the foot of the ice slope the bands became still better defined, especially upon the *southern*, or up-stream margin, narrower, more closely placed, and changed their shape from arcs of circumferences to hyperbolas. Towards the lower end of the series the bands became much shorter, the arms extending into and blending with the surface débris, and their apices appeared to mark the locus of maximum surface velocity

[1] Agassiz, *Geological Sketches*, vol. I, pp. 244 and 254; Russell, *Glaciers of North America*, p. 43; Hess, *Die Gletscher*, p. 169.

[2] *Glaciers of the Alps*, pt. II, chapter 26.

FIG. 1.—Formation of Forbes's "dirt bands," Deville Glacier, Selkirks. From summit of Mt. Fox (10,572 feet), looking eastward. Photographed, 1902, by Arthur O. Wheeler.

FIG. 2.—Forbes's "dirt bands," Victoria Glacier. Photographed from the Lefroy Glacier, July, 1904. Often confused with "dirt zones." Compare figure 2, plate XI.

of the ice. Finally the bands mingled with the superficial rock covering of the glacier and were lost. Standing upon an individual band the dark color seems to be imparted by the fine dust and sand and not by the coarser débris. In September, 1905, owing to the excessive melting of the summer, the bands stood out with unusual clearness, so that they were photographed from the side of the Lefroy Glacier, as shown in plate XVI, figure 2. By signaling to an assistant, the well defined up-stream margins of 19 of the bands were located by erecting small cairns of rock, and their distances apart, in the line of their apices, were later measured (see map, plate III). The results were as follows, beginning near the foot of the ice slope. The average interval between the bands is 97 feet.

Band No.	Interval	Band No.	Interval
Band No 1		Band No. 10	
	159 feet		100 feet
" No. 2		" No. 11	
	174 feet		86 feet
" No. 3		" No. 12	
	126 feet		88 feet
" No. 4		" No 13	
	124 feet		57 feet
" No. 5		" No. 14	
	113 feet		81 feet
" No. 6		" No. 15	
	109 feet		66 feet
" No 7		" No. 16	
	100 feet		83 feet
" No. 8		" No. 17	
	83 feet		83 feet
" No. 9		" No. 18	
	75 feet		45 feet
" No 10		" No. 19	

For reasons to be given later the writer believes that the intervals between these bands mark the annual progress of the ice down the slope, as conjectured by Tyndall, and offers the following explanation of the phenomenon. As the ice of the glacier is pushed over the crest of the ridge in its bed, which is responsible for its change in surface slope, there is formed successively a series of transverse crevasses, as explained upon page 36 of this report. The distance between these crevasses will be determined mainly by the thickness of the ice and the change in its angle of slope. Since the glacier is moving forward in winter as well as summer, although at a less rate, these crevasses must originate at all seasons of the year. Those which have been formed in the late fall, or winter, upon passing down the slope will be perfectly healed, since their lips have experienced practically no melting from the sun's action. The opposite crevasse walls come slowly together, refreeze, and leave no visible scar in the ice. Those crevasses, however, which have formed in the late spring and summer have their lips much rounded by the sun's rays. If the glacier is moving northward as in the case of the Victoria and Lefroy, the northern, or down-stream lip of the crevasse will receive the maximum effect, the southern comparatively little. Should the glacier be moving southward, the northern lip of the crevasse would still be the one most strongly acted upon by the sun, but in this case it would be the up-stream side. Glaciers flowing east or west, and having their transverse crevasses in an approximately north-south position, would have their crevasse walls affected more evenly, unless surrounding mountain cliffs interfered. In the healing of such crevasses there would be left a depression, representing the sun's action upon the lips of the crevasse, not simply for one season but through a series, and in this depression the wind-blown dust would collect and the fine débris would be washed by rain and melting ice from the adjacent portions of the glacier, rendering it lighter by contrast. Owing to the more rapid central movement of the ice the bands, at first nearly straight, will begin to curve downstream and become more and more sharply bent, their apices marking the locus of maximum surface motion. Between them will lie swellings, or ridges, having the same general form of the depressions, from which much of the finer dirt has been removed. These ridges and intervening depressions may be very inconspicuous, as upon the Victoria, or they may become very prominent, as shown upon the Deville Glacier in the Selkirks, forming what Forbes termed "wrinkles" (plate XVI, figure 1). They mark that portion of the ice which passed the crest of the slope in the late fall and winter and appear as ridges, partly because of the severe compression to which the ice is subjected and mainly because the adjacent ice has been lowered by melting. Owing to the more rapid movement of the ice down the slope the bands will be farther apart and less well defined, than after the more gentle slope below has been reached and the ice is subjected to longitudinal compression. Upon this more gentle slope they have a better chance to catch and retain the fine débris. Since the sun's action was more powerful at the center of the crevasse, the depression is greater at the apex of the band and persists after that of the extremities has been finally lost by surface melting. In consequence the bands become shorter and shorter and lastly disappear, when ablation has reduced the surface to a general slope and the fine débris is redistributed. Very often it must happen that instead of a single crevasse being formed during the season of melting there would be formed a series of them. Upon a steep slope of the Asulkan they seem to be formed in pairs as shown in plate XVII, figure 1, in which it is seen that the ridge of ice separating two adjacent crevasses is acted upon from either side and lowered, assisting in the formation of the depression. The crevasses that are forming the depressions, preparatory to the reception of the dirt, may be traced around to the almost healed crevasses at the left, while between them are seen traces of crevasses that have healed with practically no marginal melting. These are presumably those which opened and closed soon enough to escape the rounding action. If the surface slope is too great the depression produced in the ice may not be sufficient to retain enough dust to bring out the series distinctly, as is the case with the Asulkan just noted. Study figure 1, plate XXIX, from the Yoho Glacier.

That the method of formation of these dirt bands is essentially as outlined above admits of no doubt. The question as to whether they are produced annually, or at irregular intervals, needs to be investigated. The average interval of those bands originally described by Forbes upon the Mer-de-Glace was 711 feet. Opposite his station D the interval was 667 feet (*Travels through the Alps of Savoy*, p. 165). In a postscript to his volume, p. 420, he gives the move-

Fig. 1.—Formation of Forbes's "dirt bands," steep portion of Asulkan Glacier. August, 1904.

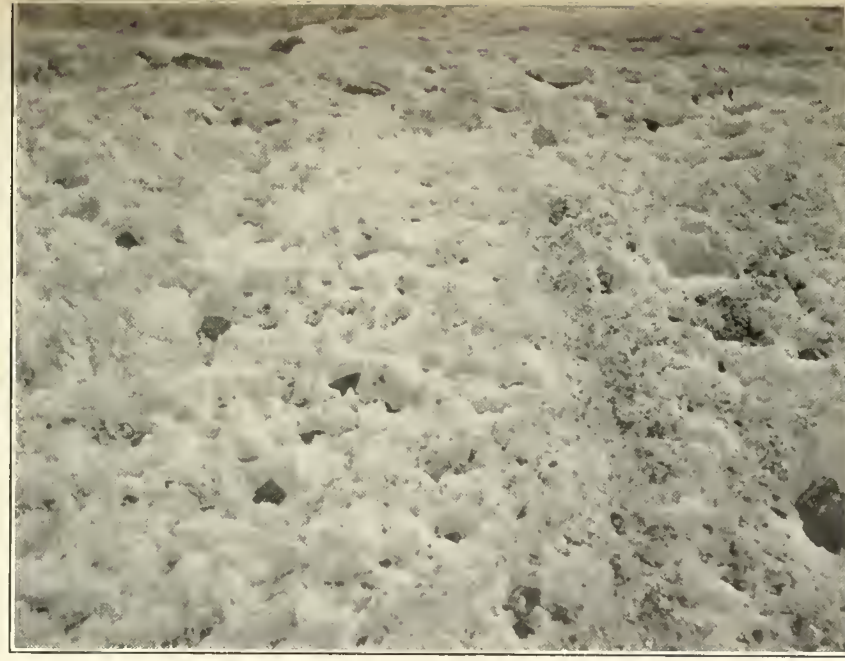


Fig. 2.—Dust wells, Victoria Glacier, the result of differential melting. In small quantities dirt facilitates melting.

Fig. 3.—Small dirt cone, Victoria Glacier. In sufficient quantity the rocky débris retards surface melting.

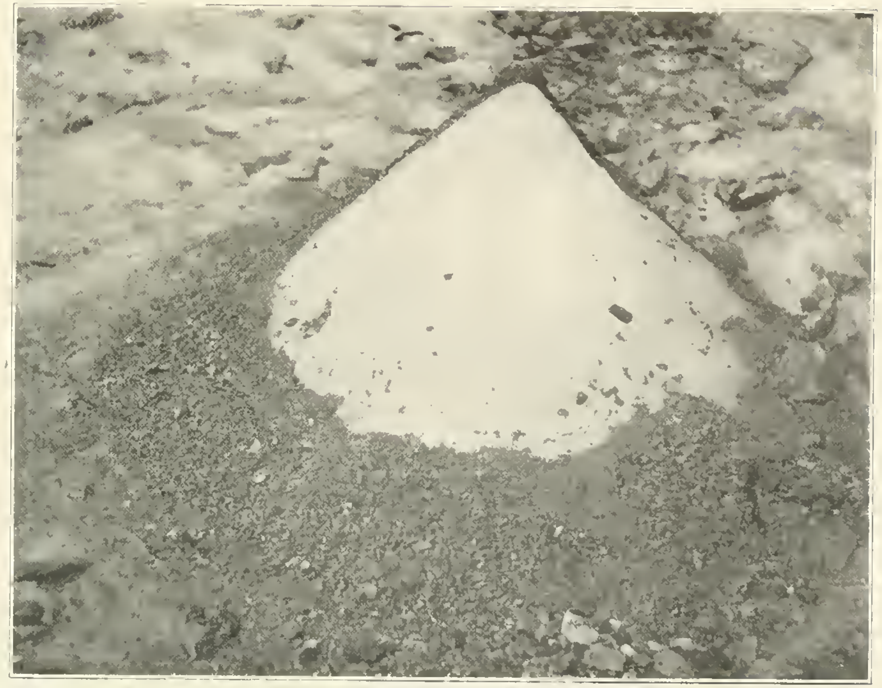


Fig. 4.—Same cone shown in figure 3, with dirt veneering removed from one side to show ice core.

ment of one of the lateral points opposite station D as 483 feet for the year and suggests that "the movement of the center is probably, at least, two-fifths greater, corresponding closely with the intervals of the 'dirt bands' of the glacier." Although the size of the intervals in this series differs plainly to the eye, still Forbes states that the difference for any one interval is probably not a tenth of the mean. From the same point of view as that used by Forbes in 1842, Tyndall counted upon the Mer-de-Glace, 17 years later, exactly the same number of bands and remarked: "The entire series of bands which I observed with the exception of one or two, must have been the *successors* of those observed by Professor Forbes; and my finding the same number after an interval of so many years proves that the bands must be due to some regularly recurrent cause." In Chapter XXXII of his *Glaciers of the Alps*, Tyndall has described his "white ice-seams," the "bandes lactées" of the French and "weissen Blätter" of the Germans. These are due, in part, to the filling of transverse crevasses, left open during the fall, with snow and then its later compression into a white vesicular ice. Since, in general, these crevasses would be those which had been acted upon by the summer sun, they would be the counterpart of the dirt bands under discussion. Sèvé found the average interval for these white seams upon the Böium Glacier, in Norway, to be 218 feet and that this represented also the average forward annual movement.[1] So far as the Victoria Glacier is concerned we have not sufficient data at hand to settle the question of the annual character of the dirt bands. At the line of plates, about a third of a mile below, the maximum annual movement of the ice was found to be 65.85 feet. The average annual interval for the lower half of the series is 76.56 feet, which is about what would be expected in the way of annual ice movement, when compared with the above. We should also expect the movement to increase as we approached the crest of the ice slope. So that the actual and relative spacing of the bands very strongly suggests their annual character. If due to some "regularly recurrent cause," as Tyndall suggests, this cause must recur with the seasons.

We are, however, not entirely without evidence that the intervals between the dirt bands indicate approximately the annual movement of the ice. As pointed out upon page 30, the Messrs. Vaux marked the location of a large boulder upon this portion of the glacier July 26, 1899. From range lines, one year later, they determined that the boulder had moved forward 147 feet. In September, 1905, this boulder was found opposite the 9th band of the series given upon page 51. In 1899 it should have lain opposite the 3rd band and, if the motion there had been the same as it was in 1904–5, it should have moved in 1899–1900 the distance of 126 feet. The previous year it should have moved 174 feet. My field notes say that the second and third bands were indistinct, so that there is strong probability that the three intervals between one and four may not have been properly distributed. The average for the three is 153 feet, which agrees very well with the actual observed motion of the boulder. If the dirt band intervals are an approximate indication of the annual ice movement

[1] Quoted from Heim's *Gletscherkunde*, p. 140.

the Vaux boulder had moved downward in 1905 from its original position some 676 feet, or at an average rate of about 113 feet per annum.

f. Dirt stripes. Somewhat closely related to the dirt bands just described, so far as their method of formation is concerned, are the fine streaks of dirt seen along the margins of most glaciers, sufficiently free from surface débris. They may be found, however, anywhere upon the glacier that the blue bands are well developed, reach the surface at a fairly steep angle and are being subjected to surface melting. The blue bands, being composed of relatively firm, compact ice, are more resistant of the sun's action, than the vesicular ice in which they are embedded and project as delicate ridges, separated by narrow furrows. Into these furrows the wind-blown dust settles and is washed from the adjoining ridges, forming narrow, parallel dirt streaks, or stripes. When well developed, as upon the Lefroy, the glacier has the appearance of having been swept with a coarse wire broom; the strokes having all been long, regular and parallel. The dirt stripes mark the position of the vesicular bands in the ice and the lighter streaks between the position of the blue bands themselves. In this way the banding is clearly shown at the surface, whereas, otherwise, it might be obscure. Views of these stripes have already been shown in plate XII, figure 4 and plate XIII, figures 1, 2. Sometimes they run down the face of a crevasse wall (plate XII, figure 4), as though they might be something more than a superficial feature, but a little chipping of the ice shows plainly that they are not. After they have once been formed the dirt stripes will absorb the sun's heat and still further emphasize the small furrows. Running, in general, lengthwise of the glacier these furrows become the sites of minute rills which have a tendency to clear away the fine dirt, as fast is it collects. For this reason, as well as because of the nature of the banding itself, the individual stripes are not continuous for any considerable distance. They are sometimes so closely placed that 10 stripes may be counted within the distance of an inch, but are usually considerably coarser.

g. Dust and pebble wells. Where small pebbles, or patches of fine dirt, often black from the presence of organic matter,[1] are thinly distributed over the surface of the ice, heat is absorbed and the ice immediately beneath is melted more rapidly than the surrounding ice. Cavities are thus formed with vertical walls, which for a time retain the water. They sink into the ice for a few inches, until protected from the direct rays of the sun by their own walls, when further melting would be delayed until the general surface was lowered sufficiently to allow the sun to again reach the foreign matter at the bottom. Such wells are shown in plate XVII, figure 2. Although their depth at any one time is seldom greater than a finger's length, still in the course of the season their total length would be 9 to 10 feet upon the Victoria and Lefroy. A thin film of water often freezes at night over the surface and then thaws out promptly when again exposed to the sun. After thus freezing the water is at times drawn into the

[1]A sample collected from the Illecillewaet in 1903 contained 14 per cent. of organic matter, enough so that when set away moist in a warm room it soon became offensive.

glacier, by means of the capillaries developed between the granules, leaving the well free from water, but with its ice cover. Where pebbles, or small dirt patches, are abundant, as shown in the last figure, the ice between the adjoining wells is melted more rapidly by the sun than it would ordinarily be, forms minute pinnacles and appears whitish and spongy. In this way the lowering of the general surface of the glacier by ablation is accelerated. By keeping itself thus at the bottom of a small well the dirt of these small patches is prevented from being blown away, or washed away, and thus it is possible that the same well may persist through, not only a season, but a succession of seasons. Should the well, however, collect additional dirt, beyond a certain limit, this excess would then *protect* the bottom of the well from further melting, the adjoining ice would soon be lowered below the bottom of the well and the well would be literally turned *wrong-side-out*. Where one has a few days to spare about the same glacier an interesting experiment would be to sift dirt into a group of typical wells, filling them to varying depths, and observing the result. Such an experiment may easily be performed upon a snow bank of sufficient depth, when it is being strongly acted upon by the spring sun. It would prepare the way for a clear understanding of the next three surface features to be described.

h. Débris cones. When the amount of dirt, sand, gravel, or rock débris, is sufficient to protect the surface of the ice from melting, or to even partially protect it, over a limited area, the surrounding ice surface will be lowered more rapidly than that beneath the protecting material and the débris will begin to be elevated, with reference to the neighboring surface. The loose débris will slide, or roll down about the side, exposing the edges and corners to the melting action of the sun, allowing still more sliding of the débris and still further melting. The ice core will finally assume the form of a ridge, cone, or mound, with its thin veneering of foreign matter, as in the case of the lateral and medial moraines already described. The companion figures 3 and 4, plate XVII, show the structure of a small gravel cone, only 15 to 16 inches in height; figure 3, as it was found upon the ice, figure 4, after the gravel upon one side had been washed off to show the ice core. It is seen what a thin covering will suffice to bring about the result. Depending upon the nature of the covering they are known as dirt, sand and gravel cones, and boulder mounds, and they may vary in height from a few inches to many feet. In plate XIX, figure 1 is shown a mound upon the Wenkchemna Glacier, estimated to be 80 feet high. This pile of rock rubbish was either dumped in a heap by an avalanche, or collected in the bottom of a lakelet, as described by Russell for the Malaspina in Alaska.[1] Cones of all types, varying in height, from a few inches to 12 or 15 feet are to be found upon the Victoria in the region of maximum melting. They may persist from one season to another, but there is a limit to the height to which any particular cone may attain. As the height of the cone grows the lateral surface is increased, over which the débris must be spread in order to suffi-

[1] *Glaciers of North America*, p. 115.

ciently protect the ice. When this covering becomes too thin, or when it is blown off, or washed down the steep slopes by heavy rains, the ice core becomes exposed and rapid melting ensues, resulting in the destruction of the feature. In case the surface covering is distributed about the base and the pure ice core exposed, the melting does not cease when the general level is reached but continues more rapidly than the surrounding ice to which has been transferred the débris. Instead of a cone, we may now get a basin-shaped depression, which is gradually extended laterally by melting, and into this depression the original material may again slide and be collected at the centre until there is sufficient to prevent further melting. An interesting and instructive experiment, in connection with that suggested upon the dirt wells, is to wash down the gravel, sand or dirt, from a collection of small cones, mark the location, and watch the changes from day to day.

i. Glacial tables. In the case of a single rock fragment, of sufficient size, resting upon the ice over which surface melting occurs, protection is afforded the ice immediately beneath. As the result of the more rapid melting of the surrounding ice the rock is relatively elevated upon a pedestal of ice and there results what is termed a "glacial table"; as seen in plate XVIII, figure 1. As the rock is elevated a short and narrow ridge of ice lying to the north of the pedestal (observe the shadow in the figure) is protected from the noonday sun, so that viewed from the east or west the pedestal is unsymmetrical. This lack of symmetry is further emphasized by the undercutting action of the rays of the noonday sun upon the southern side. Some observations were made with a view of discovering the lower limit of the rock fragments that were capable of furnishing the protection necessary to form tables. The following were found forming low tables, or starting to form them. It is obvious that the color and nature of the rock would both have their influence in determining the effect upon the ice.

Dark gray limestone,	12 x 12 x 4.5	inches.
" " "	13 x 9 x 3	"
Light " "	11 x 6 x 3.5	"
Reddish quartzite,	10 x 8 x 2.5	"
Rusted limestone,	9 x 4.5 x 1	"
Dark limestone,	8 x 4 x 2.5 to 3	inches.

In the case of the last specimen the thicker end was found to be protecting, while the thinner was inducing melting. Owing to the undercutting action of the sun's rays blocks of this size can form only low tables. Larger blocks may rise to a height of three to five or six feet upon the Victoria, the latter heights being unusual. They may persist from one season to another but there is a limit to the height which any particular table may attain, determined mainly by the size and shape of the rock. As the rays undercut, mainly upon the southern side, the block begins to lean to the south and finally topples off in that direction (plate XVIII, figure 2). The remnant of the pedestal is removed by

FIG. 1.—Glacial table, Victoria Glacier, looking southwest. Observe undercutting action of rays upon south side and shadow cast by the rock upon north side, with resultant ridge of ice.

FIG. 2.—Dethroned glacial table, Victoria Glacier, looking northeast. The boulder fallen to the south by undercutting action of sun's rays.

FIG. 1.—Boulder mound, Wenkchemna Glacier, illustrating the protective effect of rocky débris. Estimated to be eighty feet in height.

Whyte. Devil's Thumb. Bow Valley. Fairview.

FIG. 2.—Surface lakelet, Victoria Glacier, resulting from lack of débris protection. Enlargement towards right is still in progress by melting, but has practically ceased towards the left, owing to the rocky cover.

melting, the block settles into its position of equilibrium and the making of a glacial table begins anew. In exceptional cases the undercutting of the pedestal may be done by a surface stream. In the case of 25 tables selected at random, it was found that the longer of the horizontal axes of the pedestals had an average magnetic bearing of N. 36° W., or 11° W. of true north. With a larger, or a different, series, the average would probably be more nearly the true north.

j. Surface lakelets. Upon the middle portion of the Victoria, western side, where the ice is presumably quite stagnant, there occurs a series of surface lakelets, the crater-like basins of which have been hollowed in the ice. The largest of this series is somewhat elliptical in form, 200 feet long by 100 feet broad (plate XIX, figure 2), and filled with deep blue water in which miniature ice-bergs may be seen floating about. The southern and eastern banks of the lakelet are from 12 to 20 feet high and under cut, apparently by the melting action of the lake water. The northern and western banks have been acted upon more strongly by the sun, causing them to recede and the débris to slide down until the margins of the lake are filled and the ice banks veneered sufficiently to retard melting (plate XIX, figure 2). These banks are as steep as the débris can stand and from 25 to 30 feet in height. From the still steeper ice walls the gravel and small boulders are splashing into the water with a sound suggestive of considerable depth. The lake has no visible outlet and persists from season to season. Several similar lakelets, but smaller, occur in the same vicinity, some having their sides completely veneered with rock débris, which has checked melting and allowed the lakelet to become almost dry.

These lakelets may have originated in marginal crevasses and been enlarged and shaped by melting, or they may have originated by surface melting over certain limited areas less well protected by débris covering. In the preceding discussion of débris cones it was shown how miniature basins might originate. In a stagnant portion of the glacier it is possible that the basins of such lakelets might arise in a similar manner from such a mound as that figured from the Wenkchemna Glacier (plate XIX, figure 1). The rock débris rolling or sliding to the base would leave the cone sufficiently bare to permit rapid melting to a depth at which the marginal débris would begin to slide back again. The accumulation of the débris in the basin would check further melting at the center, while the surrounding ice has lost, in proportion, a part of its débris. As observed by Russell upon the Malaspina, the surrounding ice would be lowered until the basin disappeared and what had been the centre of the basin would become the crest of a boulder mound. If conditions remained favorable, *i.e.*, sufficient thickness of stagnant ice and continuous surface ablation, the sides of the mound would become more and more steep, as it gained in height and the time would come when the bulk of the débris would slide or roll to the base, the ice core would be removed to the general level and a new basin would be started. For the larger lakelets the complete cycle would probably have to be reckoned in decades and centuries.

k. Rock reflection (?). A final surface feature remains to be described, although a satisfactory explanation has not been found. Observations were begun upon the Victoria in 1904 before the winter snow had disappeared from the lower half of the glacier, which is ordinarily bare in the summer. It was noted that as the surface boulders protruded through the snow a larger percentage of them showed melted areas upon their *northern* sides, the shape and size of which sustained a certain relation to the breadth, height, shape, and possibly position of the boulders themselves. Over the melted area the snow was removed, in whole or part, to the soiled surface of the glacier, so that the feature shows with much clearness in the photographs secured. The phenomenon was seen upon the Lefroy, as well as the Victoria, and sparingly upon the Wenkchemna in midsummer, near the névé lines. The same thing was also seen upon the snow of an avalanche which had descended from Mt. Whyte and carried along some small rock fragments, which were scattered over the surface. The block shown in plate XXIV, figure 4 is a gray quartzite standing 10 inches high and is 29 inches broad. The melted area has the same length as the rock and has a correspondence in outline. The farther right hand corner of the rock is somewhat lower than the general surface and the corresponding corner of the melted area is seen to be rounded and incompletely melted. Boulders showing the phenomenon were not hard to find upon the Victoria, but were very abundant. The north-south axes of ten of the areas, selected at random, gave an average magnetic reading of N. 25.5° W., with less range than was shown in the case of the glacial tables. The magnetic declination of the region, as obtained by the Canadian Topographic Survey, is N. 25°5′ E., so that these areas are oriented with reference to the noonday sun, and might have been used for determining approximately the meridian and the magnetic declination. The natural inference is that the phenomenon is due to the reflection of heat from the surface of the boulders, this action being at a maximum when the sun is upon the meridian.

3. Former Activity.

a. Terminal moraines. Between the present poorly defined terminal moraine, described upon page 49, and Lake Louise there occurs a series of ancient terminal moraines which furnish evidence of the glacier's former extent and greater activity. The first two of these moraines are remarkable in that they consist of massive blocks of quartzite and sandrock, tumultuously heaped together and without the usual filling of gravel, sand, and clay. The position of these is shown upon the map, plate III. The spaces between the great blocks enable man, or animals, to creep in between and under them and they form an ideal home for the marmots. For moraines of a somewhat similar appearance, although probably different history, in the Mount Ktaadn region Prof. R. S. Tarr has used the expressive term "bear-den moraine."[1] The inner of these two moraines extends obliquely across the valley from the present nose, being partially overridden by the glacier and along the side of the valley nearly parallel with the oblique front. It consists of what were originally massive

[1] Glaciation of Mount Ktaadn, Maine. *Bulletin Geol. Soc. of Amer.*, vol. XI, 1900, plate 37.

blocks of quartzite, sandstone, and schist tumultuously heaped into a ridge 30 to 40 feet high. The sandstone and schist have undergone considerable disintegration, in place, forming more or less soil which supports a growth of moss, shrubs, spruce, and fir. The rings of growth, in the spruce and fir of the Lake Louise Valley, were found to average 0.884 mm., and, in the case of the averages for individual trees, to range from 0.51 mm. to 1.26 mm. As the tree matures the new rings are excessively thin; owing to the reduction in the relative amount of leaf surface, the scant precipitation, the short growing season, and the lack of direct sun light in a deep valley with a north-south trend. The largest tree found upon this moraine gave a circumference of 221 cm., at a distance of 50 cm. from the base, and should be approximately 400 years old. The material of this moraine is arranged in two main heaps, between which the glacial brook passes, that upon the eastern side having come from Mt. Lefroy and that upon the west from Victoria. After the formation of the moraine the glacier retreated up the valley to a point greater than that occupied by the present nose.

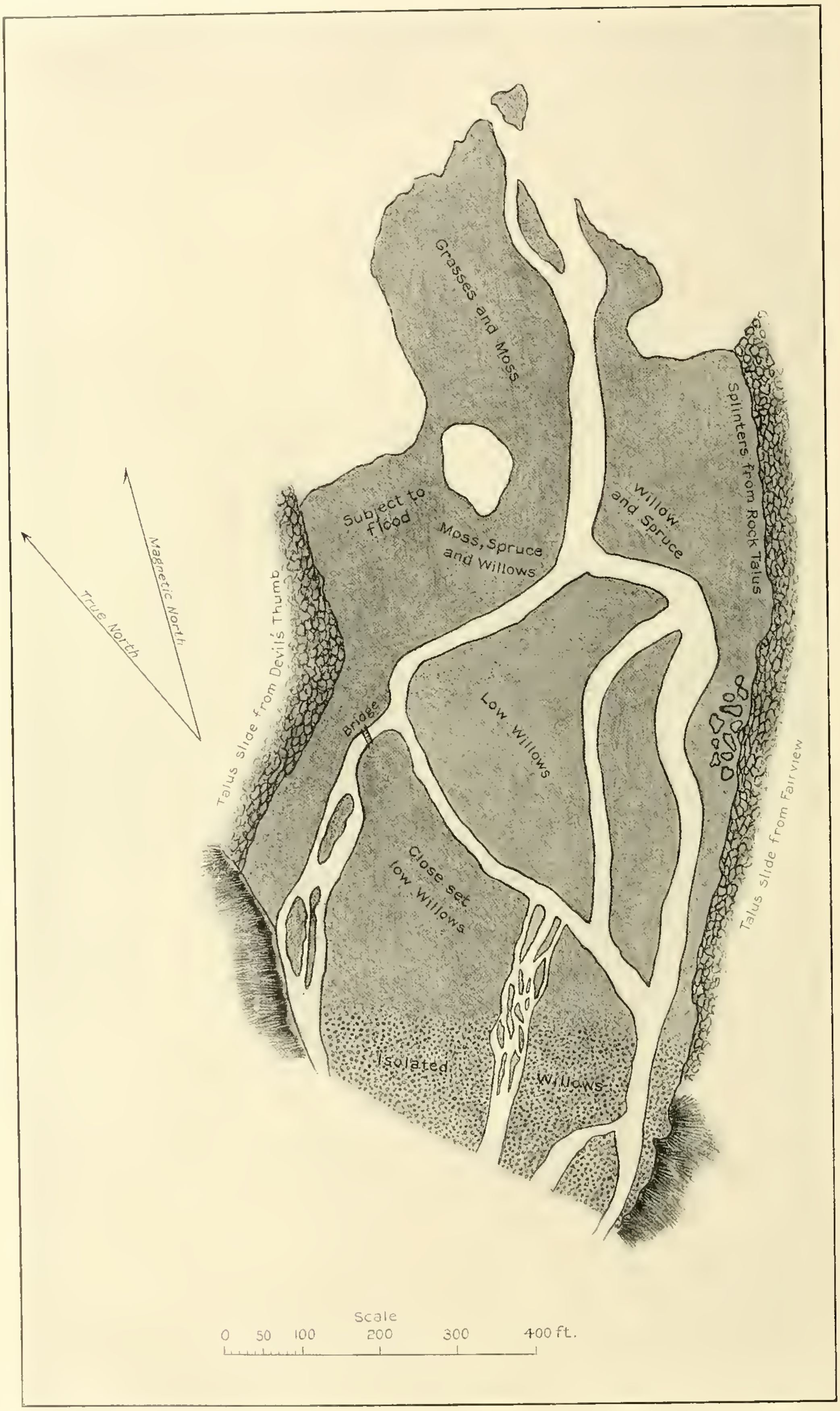
From 300 to 800 feet farther down the valley there occurs the second of this type of moraines, the blocks consisting very largely of quartzite, lichen-covered and moss-grown, but not disintegrated. As in the case of the preceding moraine the blocks are disposed in two heaps, upon either side of the glacial brook, the bulk of it lying to the west, where it forms an oblique ridge 700 to 800 feet long, with a maximum breadth of 300 feet and a height of 70 to 80 feet. Made up of such coarse blocks and with no filling of sand, gravel, or clay the whole presents a very imposing mass and impresses one with the possible importance of glaciers as geological agents. The largest block seen had split in falling, measured 31 x 25 x 15 feet, and was estimated to weigh 970 tons. The blocks are generally sharp and angular and have not been subjected to stream or ice action. They were carried either upon the ice or within it and show almost no signs of ice abrasion. An occasional single face is glaciated but in such a way as to show that this was done when, in its original position, it formed the face of the cliff. Owing to the lack of soil the growth of shrubs and trees is scant. The largest spruce seen upon the moraine itself was estimated to be 450 years old, while another just beyond the outer edge was estimated at 580 years. Upon the side of Mt. Whyte just at the line of plates, there is a large collection of similar blocks, and apparently of equal age, which appear to have become stranded here while the others were undergoing transportation. It should be noted that the present Victoria is entirely incapable of making such a moraine now, no matter how prolonged the halt. The present terminal moraine, and the oldest of the series to be described, are essentially alike but very different from these great block, or bear-den moraines. The cliffs which contributed the bulk of the material, so far as we may judge from their favorable situation and the location of the blocks, have a north-northwest trend and the blocks fell from them to the eastward.

Down the valley, a distance of one-quarter of a mile, there occurs a double detrital cone, derived from the opposite mountain slopes of Mt. Whyte and Castle

Crags. The slide from the latter slope is still in process of formation and consists of freshly broken angular fragments. That from Mt. Whyte is older and covered with spruce, fir, and willow. This material overlies, and almost conceals, a triple moraine, composed of boulders, gravel, and clay. The inner and higher ridge of the three curves regularly across the valley and in one place about 60 feet of it have been cut away by the drainage brook. It here has a breadth of 100 feet, a height of about 20 feet, and consists largely of a yellowish, stony till. Between it and the outer bear-den moraine the drainage stream has filled in with sand and gravel, forming a nearly level flat. Lower down the slope and 400 feet distant, there is another morainic ridge, approximately parallel with the first, but made up more largely of boulders while 350 feet farther on there is a third ridge containing a higher percentage of yellowish clay.

b. Lake Louise basin. This lake is roughly elliptical, with a major axis of $1\frac{1}{4}$ miles and a width of $\frac{1}{4}$ to $\frac{3}{8}$ of a mile, placed with its longer axis parallel with the valley (see plate I and plate XIV, figure 2). The chief irregularity in the outline is due to the presence of a rock slide from Mt. Fairview and to the delta deposits at the head. The level of the lake is given by the Topographic Survey as 5,670 feet above sea level. This level, however, fluctuates in the course of the season and from year to year, being some 15 inches higher in the spring, as a result of the rapid melting of the snow. Four determinations upon the inflow at the head gave an average of 80 cubic feet per second. Two measurements upon the outflow, through a rectangular orifice at the dam, gave an average of 88 cubic feet per second, the lake receiving a small additional flow from Mirror Lake and Lake Agnes. In midsummer, owing to the presence of the glacial sediment, the lake has a superb green color, but during the winter this has a chance to settle to the bottom and in the spring the color is more of a blue, the natural color of pure water.

From the studies of Mr. W. D. Wilcox, reported in the paper previously cited (page 7), the basin of the lake is seen to be a U-shaped trough, with a maximum depth of 230 feet just beyond the centre. This shows that the valley was excavated by ice and that, in all probability, the bottom of the lake is a glacially excavated rock-basin, similar to that of Lake Agnes, just west but at a higher level. Bedrock is found upon all sides of the lake, except about the foot, where there is the ground-morainic dam previously described (page 8) filling the valley to an unknown depth. At the head of the lake the valley walls are much contracted, being but 570 feet apart. They consist of a very firm quartzite, in the main, with a little slaty schist, dipping up the valley at an angle of 10° to 15°. This feature of the valley must have greatly contracted the ancient glacier passing through the gateway, caused it to thicken correspondingly and to vigorously gouge out its bed until it had a chance to again expand laterally. In this way we may account for the presence of the rock-basin, but should expect the deepest part of it to be somewhat nearer the head of the lake than is shown in Wilcox's contour map. It is not at all improbable, however, that the deepest part of the rock-basin is really so located and that there has been a



Map of delta, head of Lake Louise, by W. H. Sherzer. Plane-table survey, July, 1904. Field assistants De Forrest Ross and Frederick Larmour.

filling of the lake bed here with glacial sediment and débris from the Mt. Fairview slide, to the extent, at least, of 50 to 60 feet.

c. Lake Louise delta. After the ancient Victoria permanently retreated from the head of the lake, there began the formation, at the head of Lake Louise, of a gravel, sand, and silt delta, which is a minimum measure of the amount of glacial erosion that has since been taking place in the upper part of the valley. This delta extends into the lake 400 feet, with an average breadth of about 300 feet, as shown upon the map, plate XX, that was prepared with a plane-table in July, 1904. A shelf of fine sediment borders that portion above water and then drops off rapidly, forming a layer of unknown thickness over the bottom of the lake. Much of the delta is elevated but 10 to 12 inches above the lake level and is under water during high water stages of the lake. Portions of it are flooded during midsummer after periods of excessive melting. In this way the delta is gradually growing in height. Low, broad levees line the main stream. This comparatively small portion, which projects into the lake, is simply part of a very much more extensive deposit of glacial silt, sand, and gravel, which reaches up the valley for a distance of $\frac{1}{4}$ to $\frac{1}{3}$ of a mile and has a breadth of 500 to 600 feet. Over this very gradual slope the glacial drainage courses in three rapid, turbid streams, which unite into a single channel, 40 to 50 feet broad and one to two feet deep. Grasses and moss cover the lower, flat portion of the deposit, close set willow and spruce the central part, and isolated willows the upper gravelly region. The rock-slide from Mt. Fairview has encroached upon the lake as well as the morainic dam at the foot of the lake, upon which stands the chalet. Between this dam and the range of mountains in the background lies the Bow River Valley, which supported a great trunk glacier, leading eastward from the mountains (plate XIV, figure 2).

d. Lake Louise Valley. When the mountains were in process of making it is very probable that this valley began as a structural feature either as a trough between mountain folds, or from the opening of a joint in the rock strata. Before the coming of the glaciers it is probable that ages of stream action, aided by atmospheric weathering, deepened and broadened the original feature into a V-shaped valley. With the advent of the perennial snowfields a new geological agent entered, deepening the bed and broadening out the base so that the cross-section of the valley, particularly the lower half, assumed the characteristic U-shape of glacially excavated, or glacially modified valleys. An inspection of the general views of the valley, such as plate I, shows a lower portion with steeply inclined, nearly vertical walls, while the upper portion has more flaring walls, the arms of a truncated V. This upper portion was glaciated to a height of about 9,000 feet above sea level, or some 3,000 feet above the valley floor, the walls being smoothed and fluted and the spurs evenly truncated; see the shoulder of Mt. Fairview at the right in plate XIX, figure 2. It is not improbable that these more gentle, higher slopes represent portions of the original pre-glacial valley, produced mainly by the action of weather and running water, and not very materially modified by the ice. These slopes produced until they intersect may be assumed to represent approximately the original valley before the ice invasion. The lower portion, with the very steep walls and broad base, probably represents that portion of the valley which was profoundly affected by the great ice stream that so nearly filled the valley. The destruction of the strata necessary to secure such a result was very probably accomplished by the disrupting power of the ice, known as "plucking."

e. Ancient till sheet. The rock débris was, in great part, delivered to the Bow Glacier and carried beyond the mountains. The finer portions, consisting of gravel, sand, and clay, with some cobbles and boulders, secured lodgment in certain favorable places, particularly near the mouth of the valley, and compacted by the great weight of ice formed the ground moraine, or sheet of till. From 75 feet to 100 feet of this deposit have been exposed between the foot of the lake and the Bow River, but the maximum thickness was very probably much greater. It forms an irregular sheet, of unknown extent and thickness, reaching up to and under the modern glacier, mantling the actual rock bottom of the valley. It is entirely without stratification and the rock fragments are largely bruised and scratched. The color, as seen in the exposed sections, is a brownish-yellow, as the iron of the clay is being slowly oxydized. The more deeply buried beds would, undoubtedly, show more of the bluish-gray, which characterizes this material when it is fresh.

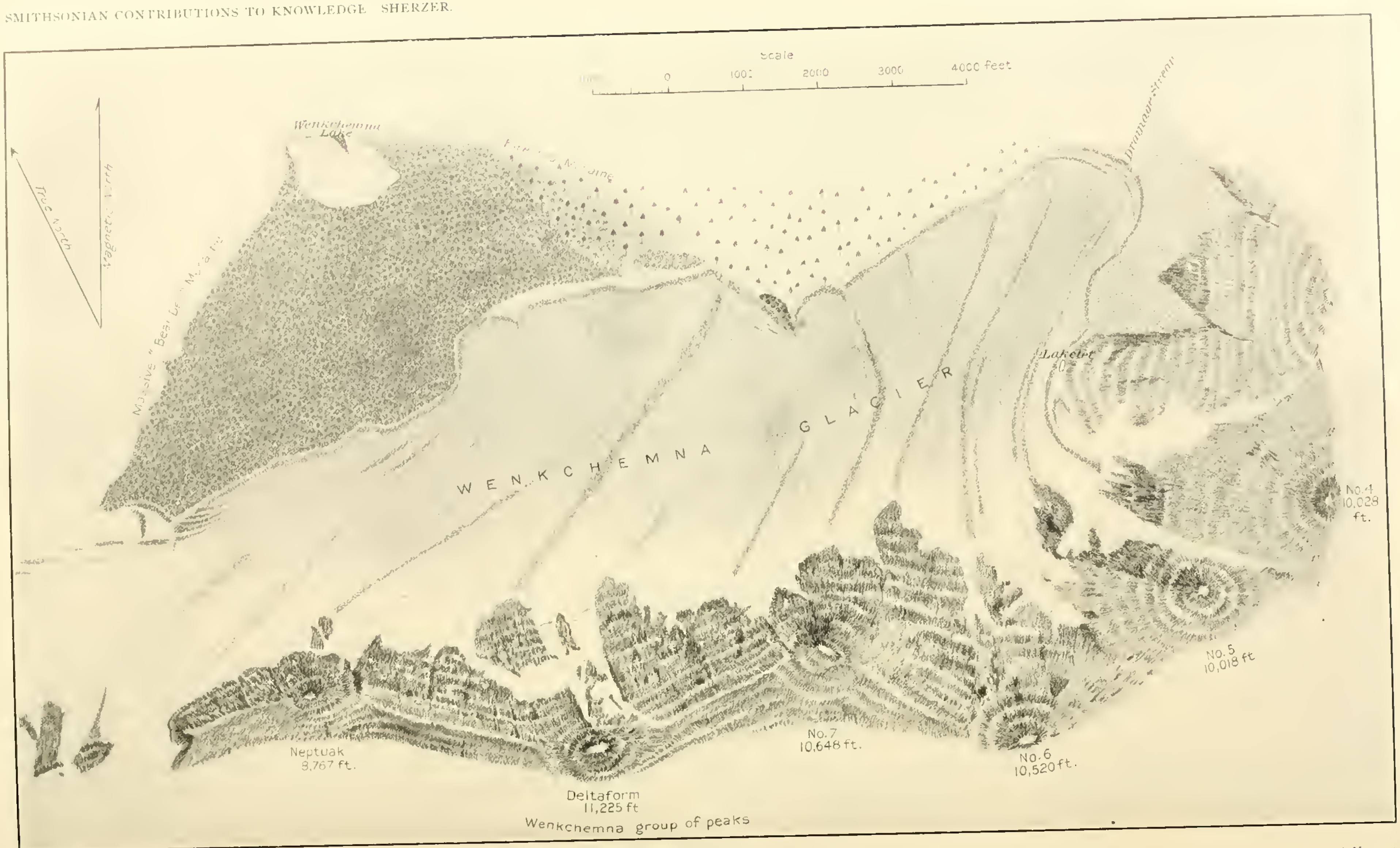
CHAPTER IV.

WENKCHEMNA GLACIER.

1. General Characteristics.

Nestling close in behind the northern base of that grand array of peaks for which the Canadian Geographic Board has recently adopted the name Wenkchemna Group lies the Wenkchemna Glacier. The name is of Sioux origin, *wikchemna* signifying ten, and was given the glacier by Mr. S. E. S. Allen, in allusion to its relation to the series of ten peaks upon which he bestowed the Indian numerals. These peaks, the highest of which has been rechristened Mt. Deltaform, with their high connecting ridges constitute here the great Continental Divide (plate xxi). Between them and Mt. Temple lies a broad valley originally called "Desolation Valley" by Wilcox, but now known as the Valley of the Ten Peaks. The glacier occupies the southern half of the upper third of this valley, and faces north, while the valley itself slopes eastward and then northeastward. In a direct line it lies only about six miles south-southeast from the Victoria, and may be reached by crossing the Mitre Pass, encircling the Horseshoe Glacier at the head of Paradise Valley and entering the Valley of the Ten Peaks by the Wastach Pass. The ordinary way of reaching the glacier, however, is from the chalet at the foot of Lake Louise, over a good trail to Moraine Lake, where a summer camp is maintained by the Canadian Pacific Railway. From

The Continental Divide, Canadian Rockies, Valley of the Ten Peaks. Photographed in 1903, from summit of Mt. Temple (11,626 feet), by Arthur O. Wheeler, Canadian Topographical Survey.



Map of Wenkchemna Glacier, Valley of Ten Peaks, Canadian Rockies. Surveyed and drawn by W. H. Sherzer, August, 1904. Field assistants De Forrest Ross and Frederick Larmour. Adjacent region based upon maps of A. O. Wheeler and D. W. Wilcox.

this camp, at the foot of the lake, the trail is rough for horses, but practicable to the front of the glacier, about two miles distant.

Quite in contrast with the Victoria, and with mountain glaciers in general, the Wenkchemna presents noteworthy peculiarities of form, in that it is very broad for its length and has a remarkable amount of frontage. Its breadth is about three miles, while its length is from one-half to one mile, the frontage amounting to something over three miles. The area of the glacier is estimated at about two square miles. It lies mainly between 7,500 feet and 6,400 feet above sea level, the easternmost nose attaining the latter elevation, or about 400 feet higher than the Victoria.

2. Piedmont Type.

The peculiarities above noted in form are dependent upon the very unusual method of formation. Instead of there being a trunk stream, to which the minor ice streams are tributary, the entire glacier results from the amalgamation of twelve, more or less, independent ice streams, each with its own feeding ground, which lie side by side. There is no propriety in speaking of these streams as *tributaries;* but since they are all nourished from the same general source, the snow which falls upon the eastern slopes of the Ten Peaks, since they coëxist, are tolerant of one another's presence, and maintain their own identity and independent velocity from névé to nose, they may be spoken of as "commensal streams," to borrow an adjective from the biologists. The form of the front, the position of the medial moraines, and the névé areas enable us to differentiate these streams as shown upon the map, and less well in plate XXI. Owing to the general slope of the valley floor, the commensal streams are deflected eastward, their natural course being northward. However, it is quite apparent that they interfere with one another's movements. The easternmost stream is relatively very small, terminating back some 3,000 feet from the nose of its neighbor, where it is forming a terminal moraine. Its neighbor to the west is narrow, but in conjunction with streams three and four, counting from the east, it reaches the general front and together they form a broad rounded nose. Number five spreads out fan-like at its lower end, and in consequence six and seven, in their lower third, are deflected rather sharply to the north. Streams seven and eight, from Mt. Deltaform, are exhibiting the greatest amount of relative activity. In the western part of the glacier the ice streams are turned eastward by the tremendous accumulation of morainic blocks which they are unable to push ahead or override. In consequence, number nine, which has only a limited collecting area, is considerably compressed, being forced laterally against its sturdier neighbor to the east. It is not likely that any one of these streams could exist by itself as an independent glacier, since it would flatten out, be more thinly clad with débris, waste more rapidly from surface and lateral melting, and disappear soon after leaving the shadow of the mountains.

This form of glacier is known as the "piedmont type," and, so far as the writer is aware, only one other example, the Malaspina, of Alaska, has thus far been described. This has a breadth of 70 miles and an average length of 20 to 25 miles, with approximately 1,500 square miles of area. It is made up of four great commensal glaciers, with an innumerable number of smaller ones. Farther west there lies the Bering Glacier, known to be of the same type, but not yet visited and described. It is quite likely that this variety of glacier is more common than has been recognized, since in addition to the Wenkchemna there is the Horseshoe Glacier at the head of the adjoining Paradise Valley, with some 16 commensal streams, and the Asulkan in the Selkirks (plate XXXIX, figure 2) which represents a piedmont glacier in process of disintegration into its component streams. If the ordinary Alpine glacier, with its tributaries, is compared to a river, the body of a piedmont glacier should be thought of as an ice *lake*, of greater or less magnitude.

3. Nourishment.

Each of the component streams of the Wenkchemna may be traced back to a more or less well defined and fairly distinct patch of névé. This may be no more than a cone of avalanched snow, or it may be a strip of permanent snow field filling a couloir in the mountain side, or between two adjacent peaks. The highest point of the Divide here is Mt. Deltaform, with an elevation of 11,225 feet, somewhat lower than Victoria. To the west, and closely connected with Deltaform, is Neptuak (Allen's No. 9) with an elevation of 8,767 feet. Eastward from Deltaform there occur in order No. 7 (10,648 feet), No. 6 (10,520 feet), No. 5 (10,018 feet) and No. 4 (10,028 feet). The northern face of this array of peaks is very abrupt, furnishing only a meager collecting area for the snow. The snowfall is probably not materially different from that at the head of the Lake Louise Valley, where it is estimated as about 25 feet annually. That which clings to the steep slopes during the winter is largely avalanched upon the glacier below in the spring and early summer. The most of that which remains is melted and but little survives the warm season. The snow accumulates along the northern base of the range, where it is protected from the noonday sun, allowing it to become converted into névé and compacted into ice. Owing to the increased altitude of the glacier's surface toward the west there is a greater deposit along the base of Deltaform and Neptuak (plate XXI). This rather meager supply of snow could support a glacier of such dimensions only because of certain favorable conditions. Being in the lee of some 3,000 feet of nearly vertical cliff, its névé field is sheltered from the noonday sun, while that portion which is exposed is almost completely veneered with a protective covering of rock débris. The form of glacier, with the ice streams lying side by side, reduces the lateral melting to a minimum, while the slope of the valley floor, upon which the glacier rests, is sufficiently gentle to allow the ice to remain in a very sluggish condition.

4. Drainage.

Because of the conditions just outlined the amount of ablation is reduced to a minimum and the surface drainage streams are correspondingly small and

FIG. 1.—Drainage brook from Wenkchemna Glacier, August, 1904. Free from sediment and having a summer temperature of 35° to 36° F.

No. 2. No. 3. No. 4. No. 5.

FIG. 2.—General view of eastern end of Wenkchemna Glacier, August, 1904. Looking southward. The very complete covering of rock débris and irregular surface are well shown.

inconspicuous. Some near the center have cut their way a few feet into the ice. None of them reach the margin of the glacier, but find their way to the base through crevasses, or moulins. Opposite peak No. 7 a small stream of pure water from the valley enters the side of the glacier. The drainage from the Wenkchemna Lake, which collects the waters from the base of Mt. Hungabee, reaches the glacier through the great accumulation of morainic blocks (plate XXIV, figure 3). No surface lakelets were observed upon the glacier, although numerous depressions occur, suggestive of the former sites of lakelets. The water is probably lacking now because of the small amount of surface melting. There was practically no marginal drainage observed. At the east end, between the side of the mountain and the glacier, there occurs a small lakelet and opposite Mt. Deltaform, at the front, there is a very shallow lakelet, or marsh, of insignificant proportions.

The various subglacial drainage streams are collected beneath the glacier into a single stream which gushes from the extreme eastern compound nose and cascades over the coarse blocks of the frontal moraine in several channels. These form a single broad drainage brook (plate XXIII, figure 1), about 100 feet across, shallow and rapid, which enters Moraine Lake one-half mile below, dropping 210 feet in the distance. The volume could not be measured, but was estimated at about 90 cubic feet per second, being somewhat in excess of the volume of the Victoria drainage brook. The volume did not fluctuate during the day nearly so much as is usual for glacial brooks, suggesting that the supply is not so dependent upon immediate melting of the ice. This is further indicated by the temperature of the water, which remained during the middle week in August very steadily at 35.6° F., and rarely varying more than 0.2° to 0.3°, no matter at what time of the day taken. September 8, 1905, it was still 35.6° at 12:30 P.M. A surprising feature of the brook is its remarkable freedom from glacial sediment, the water issuing from the glacier perfectly pure. Flowing over coarse gravel and boulders it acquires no sediment upon the way to the lake and has formed not even the suggestion of a delta at the head of Moraine Lake (plate XXV). This indicates that the subglacial erosion is practically nothing and has remained so for centuries, testifying to the sluggish condition of the glacier. In flowing the half mile to the lake the temperature of the water in August was raised from 35.6° to 36° or 37°. The lake is about a mile long, has an elevation of 6,190 feet, is apparently shallow, and filled with the purest water of an intense blue color. Passing the length of the lake the temperature in August is raised to about 44° F. The freedom of the water from sediment permits it to exhibit its natural color, a simple glance at which, as far away as the color could be distinguished, enables one to safely predict the absence of sediment from the brook emptying into the lake. Should the glacier become active and start to erode its bed the color of the lake would change to some shade of green.

5. MORAINES.

Except for the comparatively narrow strip of névé along the base of the cliff, well seen in plate XXI, the entire upper surface of the glacier is veneered with angular rock débris, effectually preventing surface melting, as already shown. This material is derived from the Wenkchemna group of peaks, through the agency of avalanches and the ordinary processes of weathering. With the entire breadth of the glacier spread out along the base of the cliff all portions receive their quota, leaving no portion of the ice exposed to the sun. The débris, at first, is covered with the snow, but it is concentrated by melting until the amount is sufficient to prevent further loss of ice at the surface when the action ceases. No ground-morainic material was observed upon the surface, in contrast with the Victoria, and this is accounted for by the absence of hanging glaciers. What might be mistaken for such upon the northern face of Mt. Deltaform, and upon either side of peaks 4 and 5 (plate XXI), are simply the continuous névé fields of the commensal streams. This method of acquiring its load leads to a somewhat irregular distribution of the rock débris, resulting in hummocks and depressions, especially towards the northeastern corner (plates XXI and XXV). These irregularities of surface are also shown in plate XXIII, figure 2. It was from this portion of the glacier that the view for plate XIX, figure 1, was taken. This irregularity of surface renders travelling across the glacier laborious and somewhat dangerous, except near the névé line. The almost complete concealment of the ice by débris renders this glacier a poor one for the study of ice structure and the usual surface features. The third ice stream, coming from between peaks 5 and 6, in the vicinity of the névé shows stratification and dirt zones to advantage, the strata ranging from five to ten feet in thickness. Low glacial tables occur here and the phenomenon described upon page 58 of this report, as possibly due to reflection of heat from the surface boulders.

The line of junction between neighboring ice streams is roughly indicated upon the surface by ridges of rock débris, somewhat low and poorly defined near the névé, but gaining in height and distinctness in their course across the glacier. These ridges are the lateral moraines of the individual ice streams and they are especially well defined over the eastern third of the glacier. Upon either side of the third stream these ridges are double for a considerable distance. Toward the western end of the glacier these moraines are neither so well defined nor so continuous and, owing to the deflection of the streams to the eastward, by the ancient moraine, swing around into a position almost parallel with the frontal. By the blending of these lateral moraines upon adjacent streams the single ridges resulting become the medial moraines of the piedmont glacier, and the outermost laterals of the two marginal streams become the laterals of the unified glacier. At the eastern end of the glacier the first stream is so short that the right lateral of the second ice stream constitutes the right lateral of the glacier as a whole. If the first stream ever extended to the front then this lateral moraine was originally a medial. A deep depression, snow-filled in 1904, separates it from the double débris cone and from the mountain spur shown upon the map. At the western side of the glacier, owing to the deflection eastward of the ice streams, there is no distinction to be made between the lateral and the frontal moraine. They end in a peculiar series of short closely pressed ridges, slightly concave outward.

Since a glacier of this kind cannot be said to have an *end*, the term frontal may be more appropriately applied to the rock débris that is being dumped along the united extremities of the individual ice streams. Were the glacier to begin a uniform retreat from its present position, there would be left a ridge of angular rock débris, over three miles in length, marking the shape and present position of the front. Inside of this would be left upon the valley floor the débris which now mantles the surface of the ice, or is contained within. Because of the very slow advance, to be noted below, the frontal morainic material over the eastern half is being very slowly urged forward, giving a steep and unstable frontal slope, but not so steep that it can not be climbed at almost any point. At only one point, nearly opposite peak No. 7, is there any ice showing and here the débris cover is partially lacking. Should the ice front actually halt a frontal moraine would form very slowly, in spite of the amount of débris carried, because of the sluggish condition of the ice. Toward the western side the front becomes less steep and high and finally merges into the névé and snow bank which mantles the col between Neptuak and Hungabee.

6. Crevasses.

The glacier is remarkably free from crevasses in the lower part and about the sides. In the case of the commensal streams, measurements would probably show that the sides were moving forward at about the same rate as the centers, so that there is lacking that differential movement that gives rise to marginal crevasses. The mutual pressure from the sides is sufficient to prevent the opening of radial crevasses along the front. The absence of prominent transverse crevasses indicates that the bed is of even slope and the motion slow enough to allow the ice to yield, without rupture, to most of the inequalities that do exist. The absence of crevasses in this case is quite as instructive as their presence would be. Upon the steeper portions of the névé slopes there occur numerous transverse breaks of the nature of *bergschrunds*, caused by the upper mass clinging, for the time being, to the rocky wall while the lower portion draws away from it. If kept under inspection these schrunds would be found to close up, as they work their way down the slope and to open again at a higher level.

7. Movement about the Front.

In a little booklet prepared for the Canadian Pacific Railway by Messrs. George and William Vaux, and entitled *Glaciers*, attention was first called to the evidence that this glacier is advancing into the adjoining forest. No data were at hand for determining the amount of this forward movement, or whether it is still in progress. Dead trunks of forest trees, from which the bark and branches have fallen, are seen projecting from near the frontal slope (plate XXIV, figure 1). Some of these trees were probably killed by a forest fire which swept through the valley 70 to 80 years ago. Other trees in similar position, but also dead, still retain their bark and boughs, but show no signs of fire. It is likely that these trees were killed, and more or less displaced, by the advance of the ice front (plate XXIV, figure 2), since which time the ice has advanced less than a dozen feet. This is still further evidence of the almost stagnant condition of the glacier. Only at one point, near the center, were there any trees which have been recently cut by rolling blocks from the frontal slope. This is taking place about the nose of the stream coming from Mt. Deltaform.

In order to gather some definite data concerning the frontal movements, a series of eight sets of reference blocks was established along the eastern half of the front, beginning at a point just east of the drainage brook. Between certain marked points upon boulders that had rolled forward and others firmly embedded in the frontal slope, accurate measurements were made with a steel tape. From August 9 to September 12, 1904, an interval of 34 days, it was found that there was no perceptible movement at the station east of the drainage brook. Passing westward along the front, and up the valley, the data indicated that there had been a wastage of the ice, causing the blocks to settle back 1.2 inches and 0.7 inch. The next two stations showed an advance of 1.9 and 1.3 inches, while the next two gave a retreat of 1.0 and 4.6 inches respectively. At the upper station, where the trees had been freshly cut, the advance for the 34 days amounted to 11.8 inches. One year later, September 8, 1905, measurements were again made between the series of blocks and at all of the stations (the upper block at station D could not be located because of disturbance) there was a small advance indicated, varying from 1.7 inches to 20.4 inches. The least movement was about the extremities of the easternmost streams and the greatest was towards the center.

A summary of the measurements is given below.

Stations.	Movement for 34 days, Aug. 9 to Sept. 12, 1904.	Movement for 361 days, Sept. 12, 1904, to Sept. 8, 1905.
Á	0.0 inches	1.7 inches.
A	−1.2 "	2.4 "
B	−0.7 "	4.8 "
C	1.9 "	12.0 "
D	1.3 "	Missing.
E	−1.0 "	3.2 "
F	−4.6 "	20.4 "
G	11.8 "	15.1 "

These figures indicate that the component glaciers are as independent in their movements as in their structure, and that some may be stationary, or in retreat, while others lying alongside are advancing. The question of the frontal behavior of a piedmont glacier is thus seen to be complicated in proportion to the complexity of its structure. Measurements made at single stations can give only very incomplete data concerning the glacier as a whole. There should be at least one such measurement for each commensal stream.

8. Former Activity.

a. Bear-den moraines. Along the western front of the Wenkchemna, for a

FIG. 1.—Front of Wenkchemna Glacier, showing its encroachment upon the forest. August, 1904.

FIG. 2.—Front of Wenkchemna Glacier, showing recent forest invasion. September, 1905.

FIG. 3.—Disintegrated sandstone blocks of ancient "Bear-den moraine," Wenkchemna Glacier.

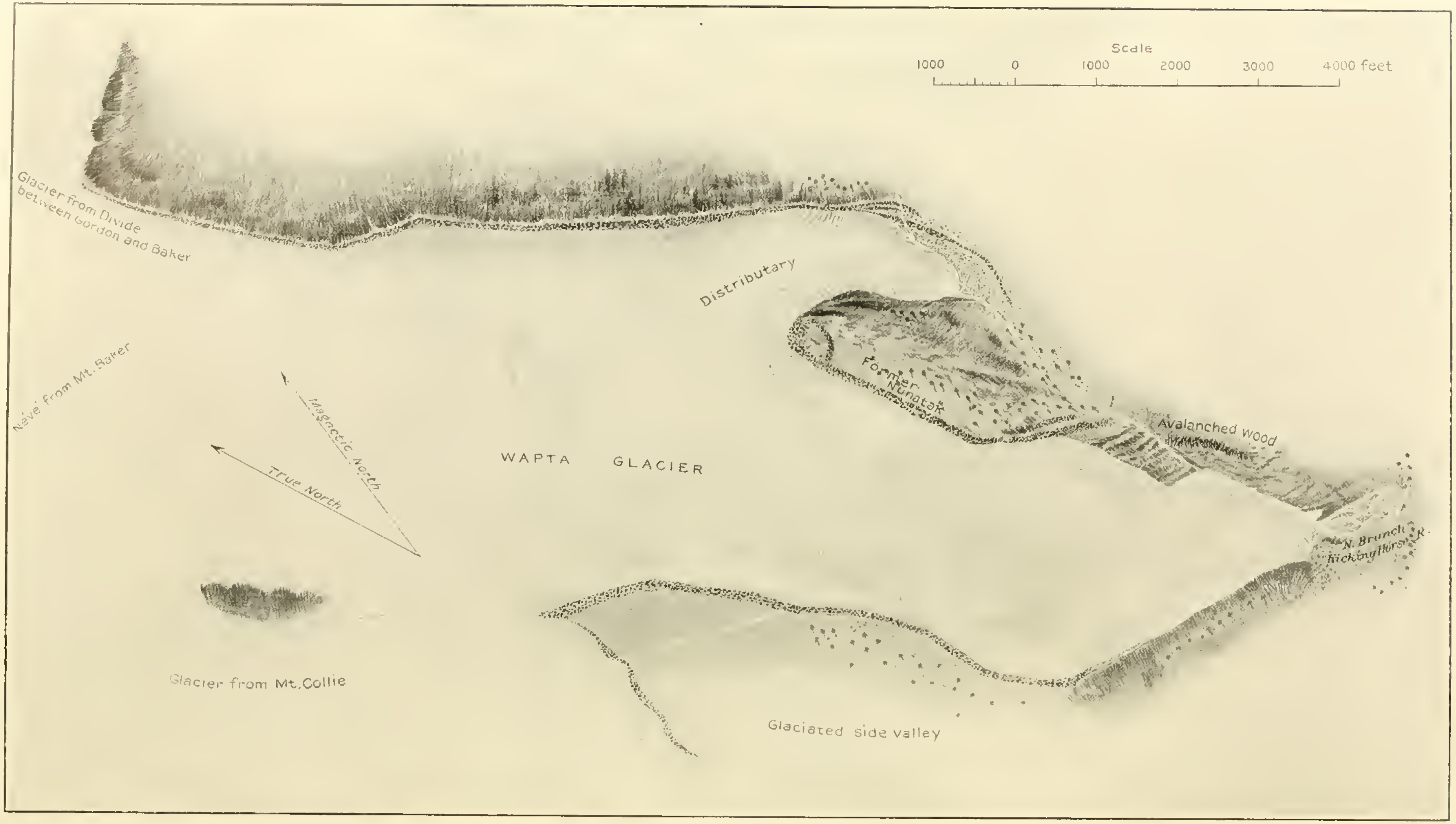
FIG. 4.—Melted area upon the *north* side of surface block of gray quartzite, Victoria Glacier, August, 1904.

distance of over a mile, there occurs a tremendous accumulation of huge morainic blocks of a red and brown sandstone. The blocks are much disintegrated by the weather, and falling apart, but each roughly indicates its former size and shape (plate XXIV, figure 3). Near the upper end of the valley the moraine is a half mile across, extending from the glacier to the foot of Eiffel Peak and almost completely surrounding Wenkchemna Lake, as shown upon the map. Toward the east the moraine becomes narrower and there may be distinguished an older portion, partially soil-covered and forested. These latter blocks are more completely coated with lichens and have plainly the appearance of greater age. There is thus evidence that the moraine was formed at two different periods, the older portion surrounding the lake and extending eastward, and that a considerable interval, as expressed in years, separated the two periods. Opposite peak No. 7 there occurs at the front an accumulation of coarse blocks, evidently part of the younger of the two ancient moraines, which the present glacier has been able to partially override. Farther west the glacier has been unequal to the task of either pushing the blocks ahead or of overriding them, and the streams have been deflected eastward, as previously noted. When the formation of the older of the two moraines began the glacier reached across the valley and deposition started. The glacier had so little depth, owing to the meager supply of névé, that it was unable to heap the blocks into a great ridge. Apparently the rather thin edge of ice was pressed against the moraine and there melted by pressure, and the blocks deposited along the southern margin until a belt a quarter mile in breadth was formed. A considerable period intervened during which time the eastern portion of the glacier had shrunken to much smaller proportions than it had formerly held and than it has at present. In a manner still to be accounted for, the glacier a second time became loaded with very coarse blocks and started to advance, possibly because of the protection afforded the surface by this load. Encountering the former moraine, however, it was unable to go over, or around, and it used its energy in a vain attempt to push the obstacles ahead. The pressure exerted caused the melting of the ice and the blocks were deposited in another broad, continuous belt, parallel with the first. As though it had learned wisdom by the experience, the glacier now rather calmly turns eastward and passes around the obstruction which it has built in its own path. These two moraines, lying side by side, are of the same type as the two described in the Lake Louise Valley, and, as far as may be judged roughly from their general appearance, of approximately the same age. The cliff from which the material was obtained has a west-northwest trend and the blocks were dropped from it to the eastward.

b. Moraine Lake. This lake has had a different history from that of Lake Louise in that it is apparently not a rock-basin and so attains no great depth. It is, however, like Lake Louise in that it has a morainic dam across its foot, although in the case of Moraine Lake the dam is of a different type. This consists of a sharply defined heap of rock débris about 400 feet long, placed at right angles to the main axis of the valley. The ridge increases in height rather gradually toward the west and attains a height of about 70 feet, ending abruptly, as steeply as the débris will stand and with no trace of any continuance across the valley. This is so unusual a feature for a terminal moraine that many are disposed to consider the mass as a rock slide from the adjoining mountain face. There are several varieties of rock represented in the heap and time did not permit an examination of the adjoining face to see whether they might have had such a source. The strata in the region, however, are so nearly horizontal that, whether the feature is a moraine or a slide, the same rocks probably occur in the adjoining mountain as farther up the valley. Standing upon the highest crest, the ridge is seen to be double, the outer one somewhat convex down stream, while from the western end there passes a short spur down the valley. The writer is disposed to accept the view of Wilcox, who gave the name to the lake, that we have here a moraine. It is, however, not of the bear-den type found farther up the valley, but very much older than the most ancient of the two. Its general lack of vegetation may be due to the scarcity of suitable soil, although it does support a sparse growth of timber. The unusual features of the mass, considered as a moraine, will be understood when the unusual nature of the glacier that formed it is considered. This represents the position of the front of the easternmost ice stream, of the ancient piedmont Wenkchemna during a prolonged period of the halt. This moraine originally abutted against a wall of ice at the west end, the side of the adjacent ice stream, which probably extended far down the valley and may have been engaged in making a correlative moraine. A relatively small amount of the débris was dragged for a short distance down stream by this neighbor, forming the spur above noted. When this ice wall melted away finally the débris rolled down and assumed the "angle of repose." As has been pointed out the present easternmost stream is short, compared with its neighbor, and were it to make a sufficiently prolonged halt there might be produced, upon a smaller scale, this identical feature.

c. Valley of Ten Peaks. The time that could be devoted to this glacier did not permit of an examination of the valley from the lake to the Bow River, or of the interesting Consolation Valley, which still supports a glacier at its head. Observations of only a general nature from the elevated trail around Mt. Temple could be made. There is evidence that the entire valley was occupied by a great ice stream, a tributary of the trunk glacier that filled the Bow Valley, the glacier then being of the Alpine type. The lower half of the valley was altered by the ice into the characteristic U-shape, while the upper half retained its flaring side walls from pre-pleistocene time. In making the bend from its east-southeast course to the northeast, the glacier pressed hard against the western face of Mt. Babel, while upon the opposite, or concave, side there was deposited a high ridge of ground-morainic material which swings around in a very regular curve from the Eiffel to Mt. Temple. From the northeastern shoulder of Mt. Temple there extends into the Bow Valley, curving gently down stream, a spur of ground-morainic material, identical with that described for the Lake Louise Valley upon page 8. This was deposited beneath the ice and along the line of junction of the

General view of Moraine Lake and eastern extremity of Wenkchemna Glacier. Published here through the courtesy of the Detroit Photographic Co.



Map of Yoho (Wapta) Glacier, head of Yoho Valley, Canadian Rockies. Surveyed and drawn by W. H. Sherzer, August, 1904. Field assistants De Forrest Ross and Frederick Larmour.

ancient Wenkchemna and Bow glaciers. Looking down the valley towards the Bow, Babel Mountain is on the right and Mt. Temple upon the left, rising above the high morainic ridge mentioned. From the shoulder of Mt. Temple there extends to the center of the view the morainic ridge reaching out into the Bow Valley, gradually losing in height and breadth. As pointed out by Wilcox, this deposit probably mantles a rock spur which escaped destruction by the ice. During the height of glaciation a tributary glacier moved in northwestward from Consolation Valley and joined the Wenkchemna at a level 400 to 500 feet above the present valley floor, forming a "hanging-valley." From the "Tower of Babel" there curves across the mouth of the valley what appears to be a morainic ridge, of the same nature and origin as that just described. The height of this hanging-valley above that of the Ten Peaks is believed by some to measure the differential erosion between the ancient Wenkchemna and that of the tributary which occupied this valley.

CHAPTER V.

YOHO GLACIER.

1. General Characteristics.

This glacier, the largest and most northerly situated of the series studied constitutes a tongue of ice from the great Waputik snow-ice field which mantles the Continental Divide to the north of the railway. Its nose lies in latitude 51° 34', at the head of the picturesque Yoho Valley, and is most conveniently reached from Field, via Emerald Lake. The day's ride, over a fairly good trail, up this ice-cut valley, with its hanging glaciers and plunging cataracts, is an experience never to be forgotten. The return trip to Field should be made over the Burgess Pass. During the summer the Canadian Pacific Railway maintains a camp at Laughing Falls, some four miles from the glacier. The glacier was first made known through the descriptions and photographs of Jean Habel,[1] secured in 1897, and each summer since it has been visited by gradually increasing numbers of tourists and students. The original name was derived from the Wapta River, another name for the Kicking Horse, the name "wapta" itself meaning river in the Stoney Indian language. The name Yoho since approved by the Canadian Geographic Board is the Indian exclamation of surprise and wonderment.

As one emerges from the forest and comes suddenly face to face with the glacier, plunging at him from above, he is greatly impressed with its size and apparent power. Its freedom from surface débris better enables it to meet the popular idea of what a glacier should look like,—the Victoria and Wenkchemna, having been somewhat disappointing (plate XXVII, figure 3) in this respect. The Yoho has the general form of a gauntlet mitten, extending in a south-southeast direction, with the *thumb* upon the eastern side of the valley and partly surrounding a great rock embossment (see plates XXVI and XXVIII, figure 2). Independently of

[1] "The North Fork of the Wapta," *Appalachia*, Vol. VIII, No. 4, 1898, pp. 327-336.

its névé it is three miles in length and for its upper two-thirds nearly one mile in breadth. In rounding the rock embossment noted it narrows to a half mile and then tapers regularly to a blunt nose. The mean elevation of the névé, according to Wheeler, is 8,400 feet, and the nose descends to an altitude of 5,670 feet. By noting the temperature of boiling water, Habel determined this elevation at 5,680 feet. The nose of the Yoho is thus 330 feet lower than that of the Victoria, and 730 feet lower than the Wenkchemna, in spite of the lack of débris covering and the southerly exposure. This is due, without doubt, to the greater precipitation and the greater size of the collecting area, by which a much larger body of ice is amassed. The mean average slope from the névé to the nose is about 900 feet to the mile; the main part of the descent, however, is in the lower half. The general inclination of the ice about the front is 20° to 25°. Upon the western side the glacier presses more or less firmly against the valley wall, except for a short distance, where the ice is steep and not to be ascended without cutting steps. By crossing the drainage stream, which is not a simple proposition unless one is mounted, one may easily ascend the glacier without the cutting of steps, the ice slope being very gentle. Skirting the crevasses and crossing back to the west side of the glacier, the névé may be easily and safely reached. Since its discovery by Habel, the glacier has maintained a great archway of ice at its lower extremity, which spans 250 feet of space, and is estimated to be 70 feet high, from which escapes the drainage. Owing probably to its southern exposure there is formed a cavern beneath the arch, as seen in plate XXVII, figure 4, extending back into the ice 100 to 200 feet, but not forming a subglacial tunnel. Toward the close of the summer season, the arch has become so weakened by melting and the formation of a transverse crevasse (plate XXVII, figure 3) that the entire structure collapses and lies a heap of azure ruins. The blocks of ice are melted down to a size that the stream can push, roll, or float, some head being obtained for the stream by the damming action of the ice débris. Finally it is all removed and the making of a new archway is started.

The actual nose of the glacier lies to the east of the archway and rests upon limestone bedrock, with only a sprinkling of ground-morainic material. Upon either side, and for some distance beyond the nose of the glacier, there is bedrock exposed, which has been smoothed in places by previous ice action and in other places roughened by plucking. Upon the western margin of the drainage brook there are shale strata upon edge which have been thus roughened. Excessively thin laminæ alternate of an intense red and yellow color. There are no reliable data for estimating the thickness of the ice, but it seems to be considerable. In the case of the Victoria and Wenkchemna glaciers the most conspicuous geological work being done is *transportation*, in the case of the Yoho we have very plainly a great engine of *erosion*.

2. Nourishment.

The collecting area of the Yoho is triangular in outline and includes the region between Mt. Collie (10,315 feet), Mt. Baker (10,441 feet), and Mt. Gordon (10,336 feet), the sides of which triangle are approximately 3 x 4 x 5 miles (plate XXVIII, figure 2). The area is located upon the western slope of the Great Divide, the crest of which extends in a curve from Mt. Baker to Mt. Gordon. The collecting area is estimated at about 6½ square miles. Upon the western slope of the Divide it presumably receives more precipitation than falls in the Lake Louise Valley and that of the Ten Peaks. From the meager data available at Field we calculated that the precipitation may amount there to 42 inches per annum, page 11. To the north it would be somewhat less and may be assumed to be 40 inches. Over the névé area the great bulk of this would fall as snow, but that which was precipitated as rain would be absorbed at once and rendered available for the glacier, representing about 33⅓ feet of snowfall each year. This amount over the collecting area, the region in which the snow is manufactured into glacial ice, would represent some 224 million cubic yards of snow, or about 24,396,000 cubic yards of ice, available each year for the Yoho. If our assumed data are approximately correct, this must represent the amount of ice to be disposed of annually by melting and evaporation. Converted into water, this volume of ice would produce 22,372,000 cubic yards of water, or 604,032,000 cubic feet of the same. Distributed over the months May to September inclusive, during which time the melting is most active, this would give an average flow of about 46 cubic feet per second. During midsummer the flow is probably four or five times this amount, due largely to the fact that the actual area drained is much larger than the single névé field, and that the melting is now at a maximum. The névé coming in from the eastern, or Mt. Gordon side, as well as that from the western or Mt. Collie side, has already been compacted into glacial ice before reaching the main flow from Mt. Baker. This ice is incorporated into the Yoho névé with whatever débris it may be carrying. The absence of overhanging cliffs about the névé area, quite in contrast with the Victoria and Wenkchemna glaciers, prevents the névé snow from becoming charged with rock débris. The glaciers from the slopes of Gordon and Collie, as well as the main stream from Mt. Baker, are carrying only subglacial material, of which we have evidence later. To this is to be ascribed the freedom of the glacier from surface débris. This condition of the ice, combined with its southern exposure to the sun, is unfavorable to the maintenance of a glacier at low altitudes. This is entirely obviated, however, by the greater bulk of ice available when this glacier is compared with the two previously described.

3. Distributary.

Except for the névé-covered glaciers above noted from Mts. Gordon and Collie, the Yoho has no tributaries; but instead, what has been termed a *distributary*, to assist it in getting rid of its ice supply. A considerable volume of ice is deflected around to the eastern side of the rock embossment and is there prematurely melted. (See plates XXVI, XXVIII, figure 2, and plate XXVII, figure 3.) This tongue of ice forms a very pretty little glacier, one-half mile long by one-quarter mile broad and tapering down to a blunt nose (plate XXVII, figure 1).

The surface is soiled with wind-blown dirt but it carries little débris. At an earlier stage it brought down from above the left lateral morainic material for the Yoho, and its ice extends still well under this ancient moraine. The axis of the glacier is curved as it is forced around the rock embossment, which it hugs closely and is still engaged in fluting and polishing (plate XXVII, figure 1). The upper crest of the rock embossment has an elevation of 6,960 feet, while that of the nose is 6,320 feet, or 650 feet above that of the main glacial stream. The average slope would be at the rate of about 1,300 feet to the mile. It is evidently in retreat although no data are available for determining the rate. In the upper portion of its course, it appears to descend over a steep step in its bed and is much crevassed. These crevasses completely heal, however, or are destroyed to their bases by melting, leaving the lower half exceptionally smooth. Over this portion of the small glacier there are developed three very pretty drainage systems, two of them marginal and the third central. The central drainage, which is collected into a trunk stream (plate XXVII, figure 1) from a network of small tributaries, has cut a longitudinal channel in the ice, and continues to a point just east of the nose. Habel's map of the Yoho Glacier shows this tongue of ice continuous around the rock embossment, forming of it a rock island, or so-called "nunatak." Such a position it originally held, but not less than 200 years ago, so far as we may judge from the size of trees growing in the valley. At a still earlier stage of glaciation the entire embossment was overridden by the ice, much of it being disrupted, wherever the ice could get a satisfactory grip upon the strata. The resistant portions were planed down, rounded, and fluted.

4. Moraines.

Because of the lack of overtowering cliffs, above noted, the general surface of the Yoho is practically free from coarse rock débris, in striking contrast with the Victoria and Wenkchemna. For the same reason also the lateral moraines are poorly developed and almost absent in the lower half mile. Upon the western margin, just before reaching a broad glaciated valley, originally carrying a tributary, the right lateral moraine begins to make its appearance and develops across the mouth of the valley into a well defined ridge of stony till, or ground-morainic matter. This ridge is continuous up the slope to the line of junction of the main Yoho with the glacier from the eastern slopes of Mt. Collie, where the latter is seen to be delivering this material from its under side to the surface of the Yoho. This ground moraine has been produced between the Collie Glacier and its bed, frozen into the ice, and urged down the slope.

The left lateral moraine begins along the southern side of the rock embossment, down in the valley, as a double ridge from which the ice has been withdrawn. It extends around the embossment, on the west side, for a distance of some 4,500 feet, developing into a prominent, high, sharp-crested ridge at the head and curving across to the eastward. This consists, also, almost entirely of ground-morainic matter, which must have been derived from the basal layers of the ice, which became stranded at the head and about the west side of the rock emboss-

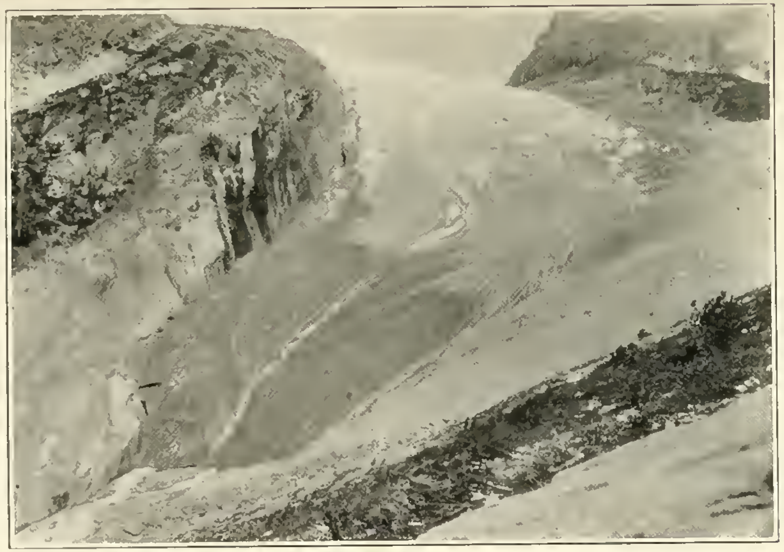


FIG. 1.—Ice distributary from Yoho Glacier.

FIG. 2.—Ice "plucking" upon a mountain peak, head of Yoho Valley.

FIG. 3.—Yoho Glacier, head of Yoho Valley. Photographed by De Forrest Ross, August, 1904.

FIG. 4.—Three-hundred-foot ice arch, Yoho Glacier, from which issues the Yoho River. Photographed by De Forrest Ross, August, 1904.

ment. In the valley occupied by the distributary described, and from 600 to 700 feet down from its nose, there begins a second lateral which curves around upon the débris-covered ice and continues for two miles along the shoulder of Mt. Gordon. This portion of Gordon has an elevation of 9,510 feet, but its cliffs do not overhang and contribute only a moderate amount of material to the moraine. A considerable portion of it consists of ground moraine which may be traced to the glacier from Mt. Gordon. This sustains the same relation to the Yoho as does the Collie Glacier upon the opposite side of the valley. Up to heights of 30 to 40 feet patches of morainic material can be seen upon the valley wall, left there when the surface of the glacier stood at a higher level. The rocks in the moraine are largely limestone, light and dark, yellow and mottled; some pieces being oölitic.

An older lateral moraine, upon the eastern side of the valley slope, may be traced for some 2,000 feet up the valley from the nose. The ridge is some 200 to 300 feet from the margin of the ice, is but three to four feet high and inconspicuous, but it has heaped promiscuously over it a mass of broken tree trunks very evidently brought down by an avalanche and heaped against the side of the ice when it stood here. The distance from the margin of the ice to the ridge, at one point, was found to be 260 feet, along the slope. The wood is somewhat decayed and gives some appearance of age. A photograph was taken when the trunks were covered with a light fall of snow, which had melted from the surrounding rock, rendering them much more conspicuous than they would otherwise be with their dark surroundings. Growing in the path of the avalanche trees were found, the largest of which gave 25, 28, and 47 rings respectively. It is likely that the avalanche occurred between 1850 and 1860, since which time the glacier has been retreating down the slope at the average rate of 5 to 6 feet per annum.

With so little rock débris carried upon and within the glacier it would require a very prolonged halt of the front in order to build up a terminal moraine of any considerable proportions. About 200 feet from the present nose, at the end of the bedrock upon which it rests, there swings in from the side a weakly developed double ridge, low and inconspicuous. It may be the correlative of the lateral moraine above noted, carrying the avalanched timber, or it may mark a still more recent halt in the general retreat. Within recent time the glacier has deposited very little ground moraine, the conditions not being favorable for its lodgment. The lowermost stratum shows upon the western side of the drainage stream, beneath the archway, and is seen to be charged with débris. Much of this is delivered to the stream and swept away by the swift current, the remainder being spread thinly over the valley floor.

5. Crevasses.

Opposite the head of the rock embossment described, the glacier and its distributary plunge over a steep step in their beds, of which the embossment itself is probably a portion which the glacier was unable to reduce to the general level of its bed. In making this rapid descent the ice is crevassed both transversely and longitudinally. The irregular blocks of ice formed melt into sharp points, or steeples, to which the term "seracs" is applied. The transverse crevasses have been noted which open just behind the archway at the nose, allowing the arch to collapse toward the close of the melting season. The absence of pressure in front allows the arch to drop forward, faster than the ice can yield to the tensional strain, and the crevasse is the result. Along both margins, for nearly the entire three miles, the normal lateral crevasses, described for the Victoria, occur. They extend inwards and upwards for varying distances, are irregularly spaced and become less numerous toward the névé, where some of them are snow-filled and snow-covered. In passing the ice cascade the ice is too much shattered to permit the formation and preservation of the dirt bands described upon page 52 of this report. However, at the crest of one of the minor slopes the phenomenon may be seen, as shown in plate XXIX, figure 1, where the depressions for three bands are plainly marked out. These mark the sites of former crevasses, and, if rightly interpreted, the distances between them show the approximate annual motion at this portion of the glacier.

6. Ice Structure.

In both the main glacier and the distributary the stratification of the ice is poorly preserved, possibly because of its destruction in passing the cascade. General views, as well as detailed ones, give almost no trace of the strata. In plate XXVII, figure 4, one stratum, relatively much charged with débris, forms the base of the arch, but does not appear upon the opposite side. This basal stratum where seen is 2 to 5 feet in thickness. Its upper surface may represent a shearing-plane, the body of the stratum being held more rigidly by its content of débris while the superincumbent ice is forced over it.[1] In places where the strata are still preserved, the dividing planes show poorly, and it is to be noted that this may arise because of the paucity of foreign material concentrated at the upper surfaces of the strata. In the case of this particular glacier the size of the névé field precludes any but the finest dust from reaching the general surface, and with so few peaks uncovered in the region the supply of dust must be meager. No opportunity was afforded for observing the structure of the névé itself. As pointed out by Reid, in the paper cited upon page 43, the basal layers of a glacier may be able to pass a cascade without suffering destruction, while the upper strata may be destroyed and in large part melted away. This may be the cause of the poor development of strata in the case of the Yoho, and the absence of the dirt zones, which should show especially well over the smooth lower half of the distributary.

In spite of the almost complete obliteration of the strata in the upper part, the blue bands are shown in great perfection where the ice presses against the west valley wall. The edges run parallel with the margin and the bands dip

[1] "The Influence of Débris on the Flow of Glaciers," I. C. Russell, *Journal of Geology*, vol. III, p. 823, 1895.

down into the ice at angles of 42°, 48°, 53°, 54°, 56°, and 61°. Upon the walls of the crevasses they may be seen to curve around into a position parallel with the valley floor. At the surface the position and approximate thickness of the bands are indicated by the dirt stripes. Differential movements of the ice, after the formation of the bands, have given rise to curved, twisted, and contorted patterns in numerous places towards the center (plate XIII, figure 2).

The fine development of glacial granules and capillaries in the Yoho Glacier has been already noted upon pages 39 and 41. They here attain the largest size of any seen in the series of glaciers studied and appear to have about the same amount of orientation near the nose.

7. Drainage.

Owing to the crevassed condition of the main glacier, there is little opportunity for the development of surface drainage streams, the water soon making its way to the bottom of the bed. In the upper portion where the crevasses are not so numerous toward the center, there seems to be too little melting to call for much surface drainage. The drainage upon the distributary has already been referred to. There enters its side a strong flow of water from the hanging-valley to the east (plate XXIX, figure 2), derived from the glaciers lying between Mt. Balfour and Mt. Gordon. Opposite the head of the rock embossment there is a short strip of marginal drainage as shown in the map, but the stream is small and the flow weak. Upon the opposite side of the valley two streams with a brisk flow enter the side of the Yoho from the broad, glaciated valley noted, while a third flows down the northern slope from the glacier upon Mt. Collie. Marginal or surface lakelets were nowhere observed. Augmented with the flow from the hanging valley, there rushes from beneath the nose of the distributary a torrent of slightly turbid water, which flows for 4,000 feet over the débris-strewn floor and enters the side of the Yoho. At the upper end of the line of avalanched wood described, this stream has cut a gorge, 40 to 50 feet deep, across a ridge of limestone strata. The gorge extends beneath the present margin of the ice and, in all probability, has been cut very largely under subglacial conditions, this part of the valley being under ice when the distributary completely encircled the rock embossment. This stream flows for 1,600 feet beneath the ice of the lower Yoho and contributes the bulk of the water which issues from the cavern at the nose, the North Fork of the Kicking Horse.[1] This stream, although shallow at first, is rapid and has a breadth of 240 feet, spreading over the gravel flat with a network of channels. About one-quarter mile from the exit the channels are collected into a single one, forming a river of very respectable size, considering its youth. The water is somewhat turbid, but much less so than that which ordinarily issues from the Victoria. This is because the drainage from the glacier itself is so largely diluted with that from the adjoining valleys, derived in considerable part from the simple melting of snow and carrying a minimum of sediment. Owing to the volume and velocity of the stream, much of the rock

[1] Marked Yoho River upon the latest maps of the Canadian Topographic Survey.

débris is carried and rolled down the valley. The channel beds are lined with coarse rounded boulders, making the fording of the stream, afoot or mounted, somewhat difficult, especially after a day of rapid melting. In the early morning the volume and velocity are somewhat reduced.

The dilution of the Yoho drainage, with that from the adjoining valleys, raises the temperature, as was noted in the case of the Wenkchemna drainage brook. The last two weeks of August the temperature ranged from 33.8° F. to 35.2° and gave an average of 34.7°. Opposite the Takakkaw Falls, about five miles from the nose, the stream has descended 770 feet and its August temperature has been raised from three to four degrees. At Field the temperature of the Kicking Horse, August 23, 1904, was found to be 44.2° F. at 5:15 P. M. On August 30, 1905, at 6:30 A. M. it was 39.6°.

8. Frontal Changes.

In August, 1901, reference marks about the nose of the Yoho were independently established by Miss Vaux and Mr. H. W. Du Bois, from which it was determined in 1904 that the glacier had receded, in the three years, a distance of 111 feet (August 16, 1901 to August 18, 1904), or at the average rate of 37 feet a year. Measured to the block of ice which had until very recently constituted the nose, the distance was 92.1 feet, of which 23 feet was for the year 1903-4, reducing the average to about 31 feet for the three years. Between August 18, 1904, and August 31, 1905, the retreat was found to have been but 9 feet. The average annual retreat for the four years 1901 to 1905 has been 30 feet. At a second station upon the western side of the drainage stream the retreat from August 17, 1904, to August 31, 1905, was 4.6 feet. From these meager data it seems that the Yoho is having its retreat checked.

9. Former Activity.

a. Moraines. Lack of time prevented any careful survey of the entire Yoho Valley from the glacier to where the valley joins that of the main Kicking Horse. No coarse moraines of the type described for the Victoria and Wenkchemna were seen and their absence is easily accounted for by noting the absence of steep cliffs about the glacier and its névé fields, plate XXVIII, figure 2. In passing up the valley the trail crosses two steep ridges, densely covered with vegetation, but these appear to be of the nature of mountain spurs, or rock slides, from the western side of the valley. About 1,000 feet from the present nose there is an interesting display of modified ground moraine, lying mainly upon the eastern side of the stream (plate XXVIII, figure 1). The structures consist of low knolls and crescentic ridges, connected with the weak lateral moraines by faint ridges. Six series may be made out, concentrically placed and with their convexities directed down stream, diminishing in height and distinctness toward the glacier. The ridges vary in height from one to twelve feet, the longest being in the form of a semicircumference with a radius of twenty feet. The ridges possess the smooth, rounded outlines of drumlins, but lack their profile

Fig. 1.—Knolls and ridges of ground-morainic material in front of Yoho Glacier. Suggestive of frontal moraines of latest ice sheets in North America and Europe.

Fig. 2.—General view looking up Yoho Valley, showing Wapta and Waputik snowfields. Photographed, 1904, by Arthur O. Wheeler, from summit of Mt. Wapta (9,960 feet). Looking north-northwest.

FIG. 1.—Formation of Forbes's dirt bands from crevasses, Yoho Glacier, August, 1904.

FIG. 2.—Hanging Valley, head of Yoho, lying between Mts. Balfour and Gordon. August, 1904.

and arrangement. They are like drumlins in that they consist of ground-morainic material, with but a thin dressing of gravel and sand. They differ essentially from drumlins in that their longer axes are parallel with the former ice margin, instead of at right angles to it. If composed of stratified sand and gravel they would be kames. In short they have the structure of *drumlins* and the form and position of *kames*. They so much resemble in miniature the knolls and ridges formed by the last great ice sheet in its retreat from the United States and Germany that their origin becomes of especial interest. They have evidently been formed by the glacier, with its nose consisting of a series of lobes, plowing into the ground moraine previously deposited upon the valley floor. A retreat occurred and then an advance, falling a little short of the first position, by which a series of mounds and curved ridges was pushed up. This was repeated at least a half dozen times, each advance being somewhat weaker and falling a little short of the preceding. Finally the glacier advanced over the entire series, but overrode them so lightly that instead of being destroyed they were simply smoothed and rounded. In melting back the last time, either from the ice itself, or from the subglacial drainage, or from both sources combined, a thin layer of sand and gravel was deposited over the structures. Had the ice lobes been larger the ridges would have appeared more nearly straight, as we find them in the case of the Pleistocene deposits.

b. Plucking action. About the nose of the glacier, as has been already noted, and upon the eastern side, toward the rock embossment, there are numerous illustrations of the bodily disruption of the rock strata, to which the term *plucking* is applied. Conditions are most favorable for this action when the strata are thin bedded and jointed, when the strike of the strata is transverse to the glacier and the dip is down stream. Under these conditions the rock layers are ripped off and the bed lowered with relative rapidity, the rock fragments being pressed into the ice and moved forward to assist in further work of a like nature. In this way portions of the bed are much *roughened* by ice action, instead of being smoothed. The edges and corners of the strata which were able, at the last, to resist the action of the ice will be found to be rounded more or less. A mountain spur, lying between the nose of the glacier and Mt. Balfour was overridden by the ice and experienced this action upon an extensive scale. The mountain is made up of curved, concentric strata, the upper layers being of a dark limestone. Upon the southern side these layers dip to the southwest at an angle of about 30°. In passing over the peak from north to south many feet of strata have been removed, those able to resist the action forming a succession of steps upon the steeply inclined slope. One only of these steps is shown in plate XXVII, figure 2, behind the hard crest of which the loose fragments have collected, while upon either side they have been swept clean by the ice. This furnishes an illustration of what is known as a "knob and tail" phenomenon. If the combined height of the successive steps were ascertained we should have a figure representing the minimum amount of this plucking action upon the southern slope, if not over the crest of the peak. It is well to note that this was done with a relatively thin sheet of ice, while in the valley bed, with some 3,000 feet additional of ice thickness, the result, under equally favorable position of the strata, would have been correspondingly greater. It seems very probable that the peculiar form of the peak Trolltinder (9,414 feet), just south of Balfour (plate XXVIII, figure 2), is due to similar plucking action.

c. Yoho Valley. There is abundant evidence that the entire valley, from the Kicking Horse at Field, was occupied by an immense ice stream, seventeen miles in length, which served as a tributary to the ancient Kicking Horse Glacier, of Pleistocene time. It, in turn, received short tributaries from the adjoining valleys and mountain slopes. The valley was filled with ice to a depth of 1,500 to 3,000 feet above the valley floor, by which the lower portion was transformed into the characteristic U-shape, seen best from below. When viewed from a height as in plate XXVIII, figure 2, the more flaring walls of the upper portion become the more conspicuous. The valley seems to have had the same general history as that given for the Lake Louise district, page 61. Being a longitudinal valley of the Rocky System, it was originally a trough between mountain folds, or a great crevasse, which collecting the drainage of the region was cut into a V-shaped valley by the joint action of running water and the weather. With the coming of the glaciers, the valley was occupied by ice and the lower one-third to one-half deepened and broadened, while the upper portion, as high as the ice could operate, was simply smoothed and subdued. Spurs were cut off and faces exposed to the action of the ice were grooved and fluted, polished or scratched.

A series of typical hanging-valleys occur along the Yoho beginning with that of the distributary, the floor of which is not yet uncovered. This ice stream has not been able to lower its bed as rapidly as has the main Yoho, and when melted back to the head of the rock embossment there will be exposed a side floor at a higher level than the main floor. However hanging-valleys, in general, may arise, this one seems certainly due to the differential effect of the two streams upon their respective beds. To the right of the distributary there extends a hanging-valley to the northeastward between Mts. Gordon and Balfour, still occupied by two glaciers, which appear to have built conjointly a double frontal moraine (plate XXIX, figure 2). This valley has a double floor, of which time did not permit an examination. From the photographs taken there appears to be a lake, occupying a rock-basin upon the lower level. About 3½ miles down from the nose of the Yoho the Twin Falls drop into the valley from the floor of a hanging-valley coming in from the west. The falls are 310 feet in height, but their crest (6,500 feet) is 1,050 feet above the floor of the main valley opposite. Five miles down from the glacier are seen the Takakkaw Falls, in the center of plate XXVIII, figure 2, the crest of which is 1,200 feet above the valley floor. The valley floor from the glacier to these falls descends about 770 feet, or at the average rate of 154 feet to the mile. These figures, based upon data supplied by Wheeler, indicate that the main valley has been lowered from 1,000 to 1,200 feet more than the tributary


True North
Magnetic North
Mt. Sir Donald
10,808 ft.
Terminal Peak
9,991 ft.
Perly Rock
7,898 ft
Bridge
1887
"Bear Den" Moraine
ILLECILLEWAET
GLACIER
Vaux line of plates July 31 1899
Aug. 6 1900
ILLECILLEWAET
NÉVÉ FIELD
7,500 to 9,500 ft
Glacier Crest
Mt. Lookout
8,219 ft.
Scale
1000
0
1000
2000
3000
4000 feet

valleys. With the effect in mind of relatively thin ice sheets upon the neighboring peaks, the writer is quite prepared to admit the sufficiency of glaciers to produce hanging-valleys, when the ice is deep, concentrated, and operates for a long period over stratified formations.

CHAPTER VI.

ILLECILLEWAET GLACIER.

1. General Characteristics.

Passing from the Rockies westward to the Selkirks, we find much evidence of the increasing precipitation; one of the first to which our attention is unpleasantly called is the tantalizing number of snow-sheds which obstruct our view. The mountains are much more completely forested than we found them in the Rockies and nearly everywhere the valley slopes are scarred with avalanche tracks. From extensive snow-fields (plate XXXII, figure 1) hundreds of tongues of ice descend to much lower altitudes than is possible in the Rockies, with their slighter snowfall. The largest of these ice tongues to be seen from the railway is the so-called "Great Glacier," or Illecillewaet,[1] the glacier that gives rise to the "rushing water." Owing to the ease with which it may be reached from the station it has been visited by more people than any other glacier in the two Americas, although, so far as known, it was not seen by the eye of white man until the year 1883. In that year it was discovered by Major Rogers, who was in search of the railway pass which now bears his name. It was originally named Agassiz Glacier by Ernest Ingersoll,[2] but this name has since been transferred to one of the commensal streams of the great Malaspina, in Alaska.

The glacier lies just to the south of Mt. Sir Donald (10,808 feet), between it and Glacier Crest, and as a great tongue of ice spills over the rim of the extensive collecting basin enclosed between Mt. Sir Donald, Mt. Macoun (9,988 feet), Mt. Fox (10,572 feet), and Mt. Lookout (8,219 feet). See maps, plate XXX and XXXIII. The glacier flows to the northwest, is but $1\frac{1}{3}$ miles in length, and in this distance tapers from a mile in breadth to a sharply pointed nose. The axis of the glacier is slightly curved, with its convexity turned toward the southwest. Lying in a broad valley with this exposure, and with no covering of débris, the glacier receives the full effect of the noonday and afternoon sun. In spite of this the nose attains the altitude of 4,800 feet, or 870 feet lower than the Yoho. Since the collecting areas are very similar in size, this difference must be due mainly to the differences in the amount of snowfall received by the two regions. The latitude of the nose of the Illecillewaet is 51° 15′, being nearly a third of a degree farther south than the Yoho. From the névé line, with an elevation of about 7,500 feet, the glacier descends 2,700 feet to the nose, or at the rate of about 2,000 feet to the

[1] This name is pronounced as though it were spelled *Illy-silly-wet*, with the stress upon the middle syllable.

[2] "The Rocky Mountains as Seen from the Canadian Pacific Railway." *Science*, vol. VII., 1886, p. 243.

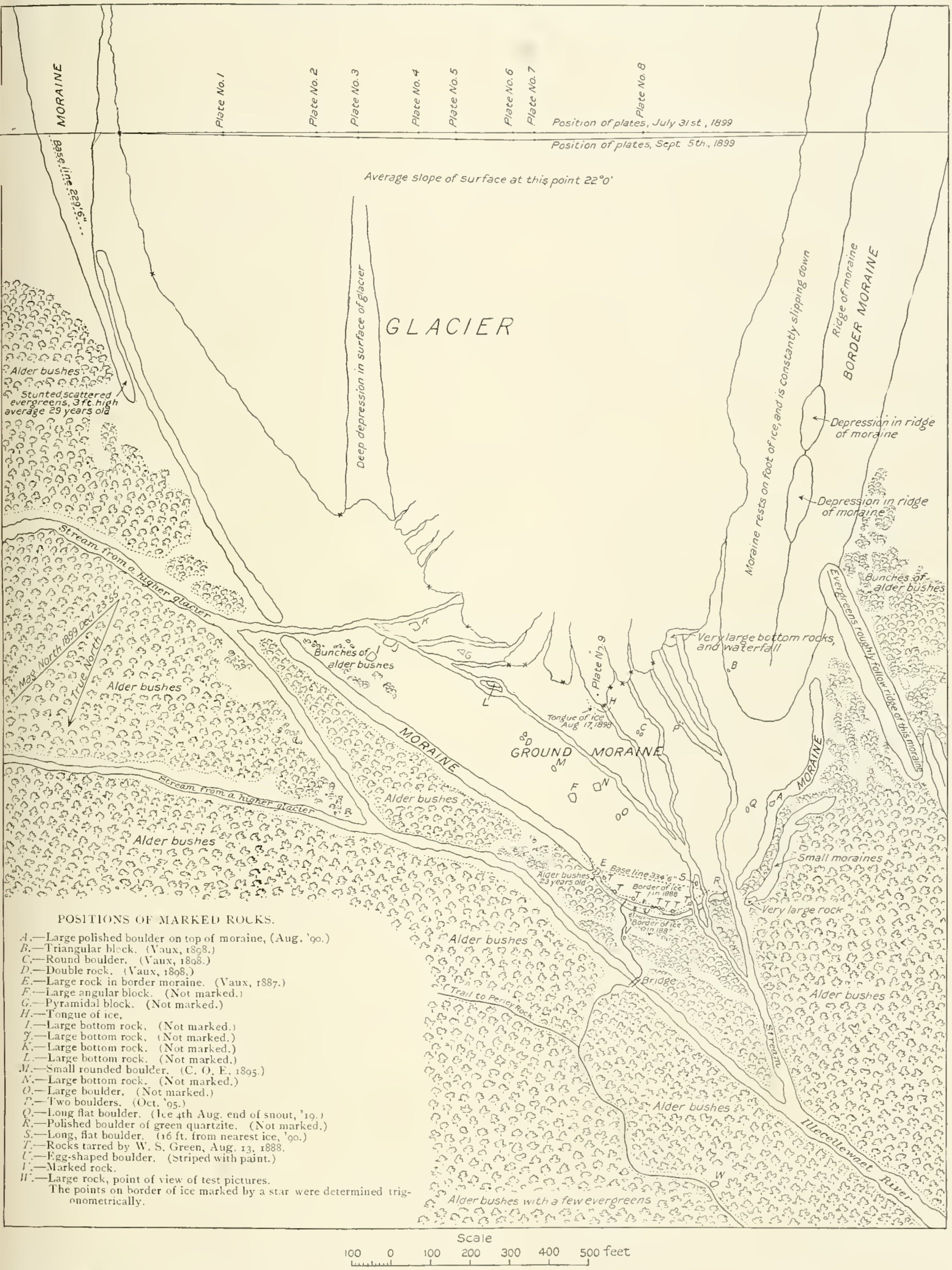
mile. The greater part of this drop is in the upper half; the glacier descending from the rim of the basin in a steep cascade, by which the ice is shattered and its original structure destroyed (plate XXXII, figure 2). In its short length the glacier receives no tributaries, but instead has a series of short distributary noses perched high up along the eastern line of cliffs leading to Perley Rock (plate XXX), with elevations ranging from 6,450 feet to 7,000 feet. No data exist for estimates upon the thickness of the glacier, but the greatest thickness of ice probably occurs below the crest of the cascade and may amount to several hundred feet.

The marginal ice is very steep upon the eastern side and for a quarter of a mile back from the nose upon the western side, so that it can not be easily ascended. Toward the nose the general inclination is about 30° to 35°, diminishing to 20° and less, so that one may mount the glacier from the nose for a short distance. The névé may be reached by a rather rough climb, either around to the east by Perley Rock, or by ascending to the depression between the glacier and the steep left lateral moraine, keeping a sharp lookout at first for rolling rock from the eastern face of the moraine. About the main nose, upon the eastern side, there occur a number of minor noses, shown in plate XXX and plate XXXII, figure 2, and also a sharply defined, trough-like depression in the surface of the ice, from 200 to 300 feet across and tapering up stream for a considerable distance. This depression appears in all the photographs taken since 1887 (plates XXXVI, XXXVII, figure 2), since which date about 400 feet of the floor immediately beneath it have been uncovered without disclosing any cause for the depression. In plate XXXII, figure 2, it appears to be continued up the glacier to the cascade and may have its origin there in some obstruction of the bed by which the ice is diverted to either side and left thinner in the lee. Just to the left of the nose there has been uncovered, since 1898, a mass of bedrock for a distance of 400 feet, its more rapid radiation of heat accelerating the melting of the ice resting upon it. The rock consists of a brownish, schistose conglomerate, furnishing an interesting display of glacial features to be described in another section of the chapter (page 95). This is the only bedrock observed in the floor of the valley from the glacier to the station.

2. NOURISHMENT.

Meteorological data at the station of Glacier House are, unfortunately, very meager. The average precipitation for the five years available amounts to 56.68 inches, of which 43.7 inches (36 feet and 5 inches), or about 77 per cent. of the whole, fell as snow.[1] Over the névé region practically this entire amount would be available for glacier formation and, as snow, would represent about 47 feet. The retangular snow-field extending from Mt. Sir Donald to Mts. McCoun and Fox is about five miles long, by two miles broad, and hence contains about ten square miles of collecting area (plate XXXIII). Of this area about two-thirds, or six to seven square miles, drains northward and feeds the Illecilliwaet, while the remainder moves southward and nourishes the Geikie Glacier, which

[1] *The Selkirk Range*, A. O. Wheeler. vol. I, p. 414.



Tongue and Moraines of the Illecillewaet Glacier, August, 1899. Published through the courtesy of George and William S. Vaux, Jr. From the Proceedings of the Philadelphia Academy of Natural Sciences, 1899.

flows westward between the Asulkan and Dawson ranges. The collecting basins for the Illecillewaet and Yoho glaciers are almost equal in size, but the estimated precipitation over the former is 41 per cent. greater than over the latter, giving a correspondingly greater volume of ice to be disposed of. This enables the Illecillewaet to attain a much lower altitude, as previously pointed out.

The mean elevation of the surface of the névé lies between 8,000 and 8,500 feet above sea level; ranging from 7,500 to 9,500 feet, not essentially different from the Yoho névé. In the central portion the névé is much crevassed, from which one may infer that the thickness of the snow and ice is not great in the basin. The surface is covered with parallel ridges and furrows, probably resulting from the rippling action of the wind while the snow was being deposited. These ridges when frozen render the walking somewhat difficult and treacherous.

3. Moraines.

a. Surface débris. Because of the wide extent of the névé field and the absence of precipitous cliffs about the margins, there is very little opportunity for the névé to acquire any rock débris. There is no evidence that any considerable quantity is gathered from the bed and carried subglacially, or englacially. It may be that the basal layers in the névé region are sluggish, or even stagnant, and that only the upper layers are being pressed out over the rim of the basin. The result of this lack of débris in the névé is that the general surface of the glacier, as in the case of the Yoho, is unblemished with rock fragments, but is somewhat soiled from wind-blown dust concentrated over its surface by melting. Some dust wells occur sparingly and a few poor examples of glacial tables.

b. Left lateral moraine. Along the western margin of the glacier fed by the ordinary atmospheric agencies of rock decay operating upon the cliffs of Glacial Crest and Mt. Lookout, there has been built up a high, sharp-crested, left lateral moraine. The angular rock fragments are supplied mainly by two prominent débris cones, which have formed upon the eastern face of Glacier Crest and which rest with their bases upon the margin of the ice, the forward movement of which has distorted the cones down stream, plate XXXII. In the summer rocks may be seen coming down these slopes, one block starting others and these still others, until a regular cannonading is in progress. As one rock collides against another with terrific force, small clouds of dust arise and we have simulated not only the roar but the smoke of battle. John Muir has given us a graphic description of the streaks of fire to be seen when these avalanches occur at night. In the way previously described for the Victoria (page 47) this material arranges itself in the form of a sharp-crested ridge perhaps 100 feet above the margin of the ice and 150 feet above the valley floor. The melting of the ice core upon the inner slope makes it steep and unsteady, while the outer has settled into a condition of more stable equilibrium and is being slowly covered with vegetation. Upon the inner slope occasional slides of the rock veneering occur, by which the ice core is temporarily exposed. The materials from the upper part and sides of the scar produced roll and slide down, collecting at the bottom and growing slowly upward until the ice is again completely covered. In this way the material is being more thinly spread over the morainic ice core and its melting accelerated. The great height which the moraine has been able to attain in its lower part is due to the fact that the glacier is unprotected by débris over its general surface, and the differential melting is so much greater than it would be if the surface of the ice were protected as in the case of the Victoria.

The material of which this moraine is composed is principally quartzite and a silvery (sericitic?) schist, with a binding of glacial sand and clay. Occasionally boulders are scratched, and are very generally bruised, with their edges and corners rounded from rough treatment they have received upon the débris cones and the moraine. About one-third of the distance along this moraine there occur two elongated depressions, exactly in the crest of the moraine. The larger and better defined of the two is 125 by 50 feet and 6 to 8 feet in depth (plate XXXII, figure 2). They are seen from a distance most plainly when the sun's rays strike somewhat obliquely, permitting the sides to cast shadows into the bottoms of the depressions. Attention was first called in print to these depressions by the Vaux Brothers in 1900,[1] showing very plainly as they do in their early photographs. Before these depressions were visited it was thought by the writer that they might represent the sites of drained lakelets, similar to those found upon the Victoria, but the explanation suggested by the above investigators seems to be the correct one. The moraine appears to have been formed of two ridges, laterally welded together, and these depressions appear to be spaces left where the two ridges did not quite meet. Owing to the sliding of the débris upon the inner slope of the moraine the basins are being obliterated and will eventually completely disappear.

Including the débris cones this lower portion of the left lateral is some 4,000 feet in length, rises to less and less height above the general ice level, and gives out for a short distance, where the ice abuts directly against the quartzite cliffs of Glacier Crest. Up to a height of 40 to 50 feet patches of morainic matter have lodged upon the rock shelves. One-quarter mile beyond, a crested ridge again makes its appearance composed of materials derived from Mt. Lookout, just to the southeast. The moraine is largely made up of quartzite and schistose boulders bound together with sand and clay and supporting a sparse growth of mosses and Alpine plants. The ridge rises to a height of 35 to 40 feet above the ice, curves around to the eastward, becomes reduced in height, and disappears under the névé, which is strewn with rock fragments derived from the cliffs of Mt. Lookout.

c. Terminal moraines. From the lower extremity of the left lateral there curve around into the valley two lower ridges, of the nature of terminal moraines. The inner and younger of these forms an inconspicuous ridge, from 6 to 10 feet high, and passes into the terminal moraine at which the glacier was found to be

[1] "The Great Glacier of the Illicilliwaet," George and William S. Vaux, Jr., *Appalachia*, vol. IX. 1900, p. 164.

FIG. 1.—General view of peaks and snowfields from Rogers Peak (10,536 feet), Selkirks, looking southeastward. Photographed in 1902, by Arthur O. Wheeler.

FIG. 2.—General view of Illecillewaet Glacier from summit of Mt. Eagle, elevation 9,353 feet, distance two to three miles. Photographed in 1903 by C. F. Johnson.

standing in 1887. From their photographs taken in this year the Messrs. Vaux have established the position of the ice front with reference to a very large boulder resting upon this moraine. This terminal ridge swings around to the north and connects with the right lateral, which is of greater age and, in the lower part at least, has lost its ice core. See plates XXX and XXXI.

d. Right lateral moraine. The ice has withdrawn from this moraine a distance of 400 to 500 feet, leaving a somewhat subdued boulder slope and a low ridge. This becomes higher and steeper as we approach the quartzite cliff which intercepts it about one-half mile back from the nose. Here the moraine is double, an older one lying just outside and parallel with it. Forest trees have taken possession of the crest and outer slope. The rocks in the right lateral are similar to those in the left and are found to be in the same condition of being rounded and bruised. Upon the rocky ledges, which carry the distributary noses referred to, there is spread out more or less morainic material, some of which has been assorted by running water. These ledges of quartzite have been much glaciated, plucked and extend up toward Perley Rock (7,898 feet). For about a quarter of a mile there extends an upper double moraine to the southeastward, where it disappears under the snow. The material consists of rounded boulders of quartzite and chloritic schist, with a filling of glacial sand. An inspection of the map shows that there is a correspondence in the arrangement and position of the lateral moraines; there being in both cases, a higher and a lower portion, separated by quartzite ledges, carrying only a sprinkling of morainic material. Since the cascade in the glacial stream lies between these exposures of quartzite it is probable that the ledges are continuous beneath the glacier; that they have proven too hard for the glacier to remove, and so it is compelled to cascade over them.

e. Boulder pavement. Between the terminal moraine and the present nose of the glacier there has been uncovered since 1887 a broad boulder belt, about 500 feet across. This consists of ground-morainic material in large part, with the rock fragments which were carried englacially, or supraglacially, and deposited as the ice front receded. These boulders have been overridden by the ice so lightly that they have not been disturbed, and yet a number of them were glaciated while in their present position, forming what is known as a "boulder pavement." About the present margin of the ice, boulders are being continually uncovered which are being subjected to the same action. The ice presses against the up-stream face of the boulder, and, either because of the warmth of the stone, or more probably because the melting point of the ice is reduced by the pressure, or because of both these agencies, an inverted trough, or fluting, is produced upon the under surface of the ice, having the form of the rock. In plate XXXIV we have these flutings shown in different stages of formation; in the last case (figure 2) the stone was estimated to lie 70 feet back from the ice margin and was under probably 50 feet of ice. Photographs taken some years ago of the "ice grotto" show that it was a feature of this kind produced by an unusually large rock. If the pressure were sufficient, the ice would settle in promptly upon the lee side of the boulder and it would be glaciated not only upon the stoss and upper surface, but upon the lee side as well. A certain relation must exist between the extent of lee-side glaciation and the thickness of the ice, which, if known, would give some data for estimating the maximum thickness of certain Pleistocene sheets.

4. Crevasses.

The crevassed condition of much of the névé, especially that in the main direction of flow, has been noted. Faultings and dislocations occur, disclosing the stratified nature of the névé and subjacent ice. This crevassing is due, apparently, to irregularities in the bed, rather than to differential motion, and indicates that the ice here attains no great thickness. About the margin of the névé field there occur, here and there, breaks where the névé has withdrawn from a portion still clinging to the rocky wall. These are the *bergschrunds*, described upon the Victoria and Wenkchemna glaciers (pages 22 and 67). On a line between Perley Rock and the western end of Mt. Lookout, there opens up a series of transverse crevasses as the ice begins its descent into the valley and its velocity is accelerated (plate XXXII, figure 2). The ice is unable to yield to the tensional strain and forms long V-shaped gashes at right angles to the stress. These become convex down stream because of the more rapid central movement of the ice. Conditions are here favorable for the formation of Forbes' dirt bands (page 50), but the ice soon plunges over the quartzite ledges, is shattered in every direction and all structure lost. Upon the crest of the cascade a network of crevasses opens, dividing the ice into irregular angular blocks. These become melted upon all sides and assume the form of pinnacles and steeples,—*seracs*,—displaying beautifully the stratified structure of the ice (plate XXXV, figure 2). Reaching the bottom of the cascade these blocks are jumbled together, many of them completely melted and the remainder frozen together into a great ice conglomerate (plate XXXV, figure 1). As pointed out upon page 44, it is quite conceivable that some of the basal layers might be able to descend the slope without having their structure destroyed.

The rapid central movement of the ice, due to the high average slope of the bed, gives rise to a very complete system of marginal crevasses, extending inward and upward, and showing conspicuously when the glacier is seen from a height. In the lower third the ice does not feel the restraint of the valley walls, spreads laterally because of its own weight, and there are opened longtitudinal and radial crevasses, some of them extending to the margin of the ice. As the surface is continually lowered by melting, only the bottoms of some of the shallower crevasses remain, and these appear simply as short gashes in the otherwise smooth surface.

5. Ice Structure.

There is evidence upon the glacier's left, back a short distance from the nose, that the stratification in the basal portion of the glacier is not completely destroyed in passing the cascade. Traces of the stratification may be seen dipping

Map of the Selkirk snowfields and glaciers, by Arthur O. Wheeler. Reproduced through courtesy of Canadian Topographic Survey, Department of the Interior. Approximate scale 1 inch = $1\frac{1}{2}$ miles. Contour interval 100 feet. Reference datum mean sea-level.

FIG. 1.—Beginning of subglacial fluting by pressure-melting, Illecillewaet Glacier, August, 1905.

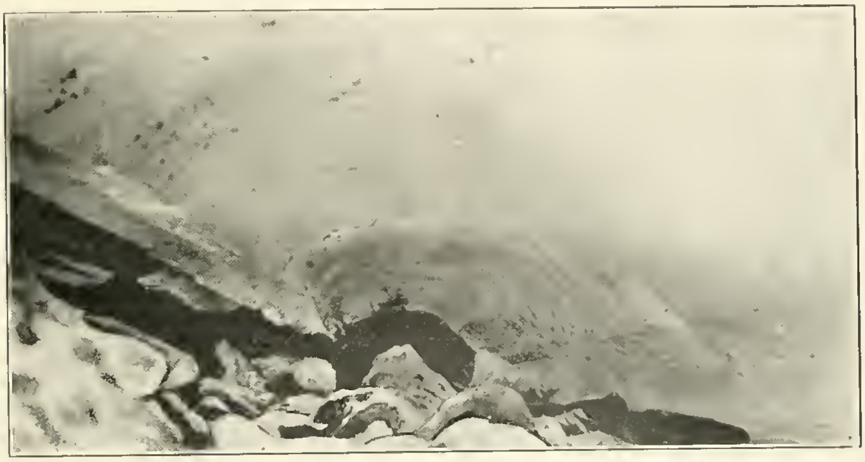


FIG. 2.—Subglacial fluting by pressure-melting, Illecillewaet Glacier, August, 1903. Photographed beneath the glacier and at an estimated distance of 70 feet from the rock responsible for the fluting.

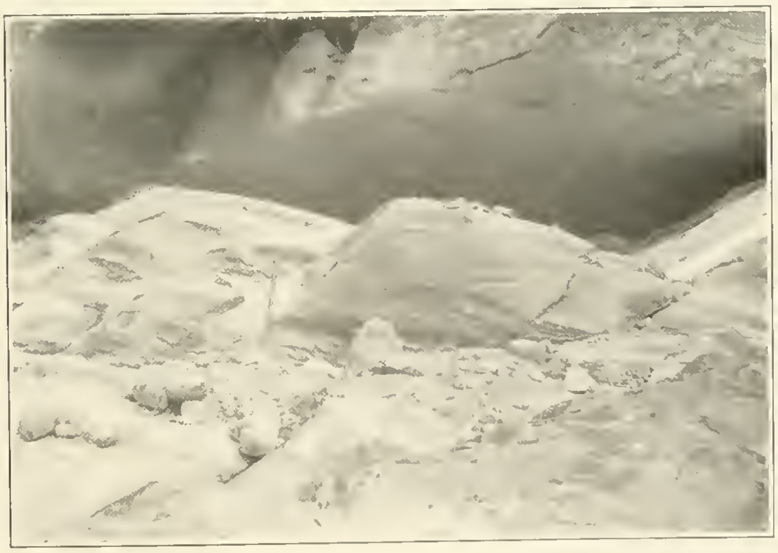


FIG. 3.—Roches moutonnées near nose of Illecillewaet Glacier. Motion of ice from right to left.

inward towards the center, this portion of the ice possibly having received less severe treatment than that nearer the center of the channel. In the case of the Yoho the question arose (page 76) as to whether the stratification was obscure because of its destruction by a similar cascade, or because of its original weak development. In the case of the Illecillewaet there is sufficient bare peak and rocky crest exposed to supply the broad névé field with successive layers of wind-transported dust and a very perfect stratification results from the concentration of this dirt at the surface of successive deposits (plate XXXV, figure 2). The almost complete lack of stratification about the nose, where it should be well displayed, along with the dirt zones, must in this case be ascribed to the cascade. The dust, originally concentrated between the strata, is brought to the lower margin of the ice, where it collects and drips as black mud (plate XXXIV, figure 1) over the valley floor. · The color is due to the presence of organic matter, of which there is enough present to render the material offensive, when set away damp in a warm room. Four determinations of the organic matter present in material collected in 1903 gave 16.75, 11.25, 10.68, and 17.23 per cent., or an average of 13.98 per cent.

It seems impossible that the coarse stratification of the ice could be so completely destroyed and the finer lamination preserved so perfectly and continuously as we should have to suppose if we referred the blue bands to the original lamination of the névé. As pointed out upon page 44 and as shown in plate XIII, figure 1, the blue bands, with the superficial dirt stripes, are very clearly shown about the nose of this glacier, from 15 to 36 being counted within the distance of a foot. They are approximately parallel with the valley floor and would probably conform with the strata, providing the latter were present. They dip inward, in general, about the nose at angles of 3° to 8°, but in places are inclined outward by this amount. As soon as the ice begins to experience pressure from the moraines, or the valley walls, the blue bands become more and more steeply inclined, beginning with angles of 8° to 16° and increasing up the valley to 70° to 75°. The relation of bands in the ice to the stones which are fluting the under surface (plate XXXIV,) has been discussed upon page 44.

The glacial granules, with the melting phenomenon described in connection with the Victoria Glacier, are well shown about the nose. In size they stand next to those of the Yoho and range from the size of hickory nuts to that of hen's eggs. They are limited largely to the blue bands, or the white seams that intervene, but in cases are seen to cut across from one to the other. As the granules assume distinctness the blue bands become more and more obscured. Between the granules there is developed, under suitable melting conditions, a very perfect and beautiful network of capillaries described upon page 41.

6. Drainage.

a. Surface and marginal drainage. Upon the nights of September 7–8 and 8–9, 1904, the minimum temperature of the ice was measured by inserting a thermometer to the depth of twelve inches in the face of a crevasse near the nose.

The two readings were 32.0° F and 31.9°, indicating that this portion of the glacier was very near to its melting temperature. Before liquefication, however, can occur a large amount of heat must be rendered latent, when water is produced with the same temperature as that possessed by the ice just before melting. The heat necessary for this conversion is supplied in the main directly from the sun but in part by that of the atmosphere, rain, friction and pressure of the ice against the valley floor and sides, and whatever heat may be reflected, radiated, or conducted, from the same source. Almost without exception the surface drainage was found to have a temperature of 32°, varying but a very small fraction of a degree from this. The surface ablation is rapid during the summer, owing to the exposure of the ice to the sun and the absence of protective débris.

As would be expected from the greatly crevassed condition of the ice, no surface streams of any size can develop, either over the general surface or along the margins. Small streams flow directly to the ice margins and cut channels, in a few cases, to the depth of a foot. This water may be absorbed at once by the loose materials covering this portion of the bed, or it may collect and give rise to scant marginal or subglacial drainage streams. These flows soon cease when the sun drops behind Glacier Crest and throws the glacier into shadow. In 1904, for a distance of some 500 feet, a small drainage stream was found between the left lateral and the adjoining ice slope. Since the ice of the glacier is here continuous with the morainic ice core, this stream was a surface rather than a marginal one. From the lower end of this moraine there occurred also two small flows of water, apparently coming from englacial channels in the moraine. After a six hours' rain, September 8, 1904, during which 0.58 of an inch of rain fell, the water of these streams was rendered muddy, while the turbidity of the main glacial flow was not perceptibly affected.

b. Terminal drainage. Upon the eastern side of the glacier, drainage streams leave the ice margin in the neighborhood of the elevated distributary noses, as shown upon the map. The ice here rests upon bedrock and the streams have sought the lowest depression, there being three such which are draining this portion of the glacier. The westernmost of these breaks into a network of streams upon emerging from the ice, and cascading over the rocky ledges again enters the side of the glacier, to reäppear at the nose. The two other streams have cut gorges 50 to 60 feet deep across the hard strata, showing that they must have been at work for considerable periods, probably as subglacial streams. However, the high velocity of the water and the sharp glacial sediment enable it to work very effectively, even upon quartzite. These two cascade over the ledges and unite some 1,600 feet down into a single stream, which receives tributaries from the slopes of Sir Donald. Just outside of the right lateral moraine the stream divides into numerous branches, which reunite upon the gentle gravelly slope and form what is known as a "braided stream." Eastward of the upper, right lateral moraine, between it and Perley Rock, there is a deserted gorge, similar to those now being formed, partially filled with gravel and morainic matter. The drainage has been deflected westward to a lower level.

FIG. 1.—Regelation of ice blocks at foot of ice cascade, Illecillewaet Glacier, September, 1904.

FIG. 2.—Stratification in upper part of Illecillewaet Glacier.

In 1904 there issued from the main nose of the glacier five drainage brooks, the main one lying to the west of the nose and receiving the drainage from the left lateral moraine. This stream follows the inner curve of the terminal moraine and cuts across it at a point opposite the nose. The other four streams form a network over the boulder pavement, unite into a single stream, which makes its way across the terminal moraine and joins the main flow. About 1,200 feet from the nose of the glacier (1904) this drainage brook from the lower and west side of the glacier unites with the strong flow from the eastern side of the valley and together they form the Illecillewaet, or "Rushing Water," a tributary of the Columbia. The average flow from the glacier is not much different from that of the Victoria and Wenkchemna, but considerably less than that from the Yoho, which collects the drainage from a larger territory. Based upon the estimated size of the névé area and the average annual precipitation, the average flow for the months May to September, inclusive, should be about 65 cubic feet per second. Owing to the somewhat larger drainage area and the more rapid midsummer melting the flow seems greater than this in July and August. The water, as it issues from beneath the nose, is only slightly turbid compared with the Victoria, indicating a small amount of subglacial erosion. The color becomes slightly green in the combined streams and still more so after it has received the Asulkan drainage farther down the valley. With the loss of sediment, which is gradually stranded here and there, the water assumes a bluish tinge, except where lashed into foam.

c. Temperatures. During the last week in August and first week in September, both in 1904 and 1905, some 30 observations were made on the temperature of the drainage at the nose. The average temperature, taken at various times of the day, was found to be 33.1° F., with a range from 32.4° to 33.8°. That from the eastern side of the valley, taken just under the bridge on the trail, gave an average of 39.9°. One-third of a mile down the valley, at the lower bridge across the stream, the average temperature of the combined streams was 38.3°, ranging from 34.9° to 40.6°. Where the Illecillewaet passes beneath the railway, having received the Asulkan brook, four observations upon the temperature gave an average of 39.7 °.

7. Forward Movement.

As early as 1888 observations were made by Rev. W. S. Green to determine the forward movement of the glacier. On August 13, he set three poles in the ice by boring holes with an auger, the distance from the nose not being given.[1] These were visited upon the 25th of the same month and were found to have fallen, owing to surface melting. The holes were, however, found and the poles reset for measurement. The distances moved in the twelve days are recorded as follows: "No. 1 pole, near moraine, 7 feet; No. 2, further out, 10 feet; center of glacier, 20 feet." For the middle of the glacier this gives an average daily motion of 20 inches. About the margin of the ice Green, at the same time,

[1] Among the Selkirk Glaciers, 1890, p. 218.

tarred a number of boulders in closest proximity to the margin, which rocks could still be indentified in 1905. (See rocks marked T, plate XXXI.)

In 1899 George and William Vaux set a line of 8 steel plates across the glacier, some 1,400 to 1,500 feet back from the nose, their line lying somewhat obliquely to the main axis of the glacier (see map). The average surface slope was given as 22°, and the distance across the glacier along the line of plates was 1,720 feet. A base line was laid out along the higher portion of the right lateral moraine, 229.5 feet in length, and the plates located by triangulation, July 31, 1899. Bearings were taken upon the plates August 11, 1899, and September 5, 1899, the latter work being done by Messrs. H. B. Muckleston and C. E. Cartwright, of the Canadian Pacific Railway. One year later (August 6, 1900) the plates were again located by the Messrs. Vaux and their forward movement for the 372 days determined. The following table is based upon their data published in *Appalachia*, vol. IX, 1900, p. 160, and the *Proceedings* of the Academy of Natural Sciences of Philadelphia, March, 1901, p. 215.

TABLE VII,

OBSERVATIONS UPON THE LINE OF STEEL PLATES SET ACROSS THE ILLECILLEWAET GLACIER, JULY 31, 1899.

(Total Distance across Glacier along Line of Plates 1,720 feet.)

Plate.	Distance from East edge.	July 31 to Aug. 11, 1899.		Aug. 11 to Sept. 5, 1899.		July 31 to Sept. 5, 1899.	July 31, 1899 to Aug. 6, 1900.	
		Total motion, 11 days.	Average daily motion.	Total motion, 25 days.	Average daily motion.	Average midsummer motion, 36 ds.	Total motion, 372 days.	Average daily motion.
	Feet.	Feet.	Inches.	Feet.	Inches.	Inches.	Feet.	Inches.
1	265	3.54	3.86	2.62	1.26	2.56	88.6	2.86
2	500	3.33	3.64	8.67	4.16	3.90	124.0	4.00
3	605	6.25	6.82	8.75	4.20	5.51	139.7	4.51
4	750	6.21	6.77	——	——	6.77	181.0	5.84
5	845	5.96	6.50	11.71	5.62	6.06	188.0	6.07
6	980	6.37	6.96	13.79	6.62	6.79	197.0	6.36
7	1040	5.00	5.45	14.33	6.88	6.16	158.5	5.11
8	1310	5.50	6.00	——	——	6.00	170.0	5.48

An inspection of the above table shows that the maximum movement, for both the summer and the entire year, lies well to the west of the axis of the glacier. The greatest average daily movement was made by plate 6, which lies 120 feet to the west of the center, while plates 7 and 8 show only slightly less movement. This is in harmony with what is known concerning the flow of glaciers on a curve, the maximum movement taking place not at the center, as in the case of the very straight Victoria, but lying between the center and the convex side. The average daily movement of plate 6 for the year is 94 per cent of its summer motion, as compared with 81 per cent for the corresponding plate upon the Victoria. For some reason, not easily explained from the data at hand the mean summer motion of the two most easterly plates was less than their yearly average. It is to be noted that the maximum summer movement of 6.96 inches (July 31 to August 11), 1899, is but about one-third of the maximum movement observed by Green in 1888 (August 13 to 25). The only way to reconcile the two results is to suppose that Green's measurements were made farther up the slope towards the cascade, where the movement is undoubtedly much greater than towards the nose. Messrs. Vaux placed a ninth plate upon the nose of the glacier and had it under observation from August 1 to August 20, 1899. The average daily horizontal motion for the first two intervals between measurements was 5.9 inches and 5.0 inches. A crevasse then formed, detaching the block carrying the plate, and the subsequent apparent motion was 2.8 inches and 2.7 inches daily.

8. Frontal Changes.

a. Recession data. Owing to the easy accessibility of the glacier and its attractiveness to the ordinary visitor, we have more data from which to determine the frontal behavior of the Illecillewaet than any of the other Canadian glaciers. As has been noted, from the photograph taken in 1887 by the Messrs. Vaux the position of the ice at that time, with reference to a large boulder, was determined and in 1898 marked conspicuously. In 1888 the margin of the ice was marked by Green and the glacier was photographed by Notman & Son, of Montreal (plate XXXVI, figure 1). Reference blocks were marked in 1890 and 1895 by interested visitors. A visit was paid to the glacier September 3, 1897, by Albrecht Penck, of Vienna, and a sketch made of the tongue of the glacier and its relation to the lower moraines. This was published in the *Zeitschrift des Deutschen und Österreichischen Alpenvereins*, Jahrgang 1898, Band XXIX, s. 55, under the title "Der Illecillewaetgletscher im Selkirkgebirge." The height of a number of points was determined by an aneroid and four reference blocks established and located upon the map. These blocks were left to be marked by a railroad employee, but were apparently neglected and in 1904 could not be identified with absolute certainty, owing to the changes in the ice margin. Based upon the railway elevation at the station, Penck determined the elevation of the nose in 1897 as 4,793 feet (1,461 meters). The foot-bridge, just beyond the modern terminal moraine he gives an elevation of 640 feet above that of the station, or above sea level 4,760 feet,[1] and this he uses as his datum for elevations about the glacier. The nose of the glacier at this time lay 33 feet above the floor of the bridge, and the crest of the adjoining lateral just opposite was 131 feet above the valley floor at the nose.

In the year 1898 a number of reference blocks and range lines were established by the Messrs. Vaux and have since done excellent service in measuring the frontal movements. In August, 1899, they made a very detailed survey of the nose and adjoining region and prepared a large scale map which is of the greatest

[1] The correction of the railroad levels reduces this elevation by 27 feet, giving the bridge-floor 4,733 feet.

value in the determination of changes in progress[1] (see plate XXXI). They have very carefully located upon their map the reference blocks established by themselves and others, so that they may be readily found upon the ground. To their untiring zeal and devotion to the cause we are very largely indebted for our knowledge of the behavior of the Illecillewaet front since the year 1887. From their reference blocks the writer took measurements in 1902, 1903, 1904, and 1905, and in 1904 established four other reference stations about the side from which to determine the marginal changes.

There is reason for thinking that the glacier in 1887 was just completing a rather prolonged halt at the younger of the frontal moraines described. That it had not recently extended much beyond is proven by the size of the alder bushes growing about the outer slope. That it had made a rather prolonged halt at this line, either at this stage or a previous one, is shown by the size of the moraine, which, with the small amount of débris carried by the glacier would require a considerable time in building. From the early photographs it is seen that the glacier was much bulkier and broader at this stage and the slopes about the nose much steeper, enabling the glacier to maintain well its position at the moraine (plate XXXVI, figure 1). During the year 1887 to 1888 it had begun to withdraw from the moraine, as shown clearly in the Notman view just referred to and as indicated by the rocks blotched with tar by Green. The retreat began somewhat gradually and attained its maximum between 1890 and 1900, averaging for these ten years about 53 feet per annum. The average for the opening lustrum of the century is 19.6 feet, the retreat being reduced until it amounted to but two feet for the year 1904-5. For the 18 years from 1887 to 1905, the horizontal retreat from the Vaux reference block was 597.5 feet, or at an average yearly rate of 33.2 feet. It should be noted, however, that this measurement is not in a line with the main axis of the glacier. The available data concerning this glacier are given in summarized form below. The measurements were taken variously, most of them between the middle of August and the middle of September, so that the retreat assigned to some years, may belong in part to the preceding, or the following year.

Recession Data of the Nose of the Illecillewaet Glacier.

1887–1888.	10 to 15 feet.
1888–1890.	Average rate about 23 feet
1890–1898.	Average rate of 56 feet.
1898–1899.	16 feet.
1899–1900.	64 feet.
1900–1901.	15 feet.
1901–1902.	48 feet.
1902–1903.	22 feet.
1903–1904.	11 feet.
1904–1905.	2 feet.
1905–1906.	84 feet.

[1] "The Great Glacier of the Illicilliwaet," George and William S. Vaux, Jr., *Appalachia*, vol. IX, Mch., 1900, p. 156.

FIG. 1.—Illecillewaet Glacier in 1888. Photographed by Notman & Son, Montreal.

FIG. 2.—Illecillewaet Glacier in 1905, from approximately the same view-point as figure 1.

Upon the face of the bedrock exposed near the nose a mark was established September 16, 1903, immediately beneath the nearly vertical side of the ice, the height of which was estimated as 60 feet. August 24, 1905, it was found that the ice had withdrawn laterally 2.4 feet from the face. Passing around from the nose eastward, three stations were established along the margin of the ice. A large boulder was found just emerging from the ice, the first week in September, 1904, and marked "Face emerging, Sep., '04." Upon the 24th of August, 1905, it was found that the ice had retreated here 14 feet. Farther along a medium-sized boulder had been marked in 1903, "15 ft. to ice. IX–16–03." By September 1, 1904, a retreat of 12.5 feet had occurred here, while at the upper station the boulder "27 ft. to ice. IX–16–03," measured September 3, 1904, 27 feet, and August 25, 1905, 27.1 feet. These data indicate that the margins of the ice have been receding as we approach the nose, more rapidly upon the eastern side, but that farther up along the margin there has been no change for the last two years and, very probably, for a considerably longer time The two views on plate XXXVI, taken from almost identically the same view-point, the former in 1888 and the latter in 1905, furnish a good opportunity for noting the changes produced in the glacier in the 17 years. It seems almost possible to recognize the individual trees standing to the right of the center, but the lower half of the glacier is unrecognizable. A stadia and trignometric survey of the Illecillewaet and Asulkan glacier tongues was made in 1906 by the Messrs. Vaux and a report made to the Philadelphia Academy of Sciences. Some additional data concerning the movements of the steel plates upon the Illecillewaet were collected and appear upon plate XXX of this report.

b. Ice waves. In comparing their photographs made in 1898 and 1899 from a certain large boulder, just west of the trail, Messrs. Vaux noted an apparent thickening in the ice just beneath the névé line. By drawing a delicate line between corresponding points in figures 1 and 2, plate XXXVI, that may be recognized in the upper névé region, it is seen that the ice margin along the sky-line stands slightly higher in the 1905 view. The difference is slight, however, and can represent but a few feet. When the Notman view of 1888 is compared with a second, which was made in 1897, and here reproduced in plate XXXVII, figure 2, the heaping of the ice line beneath the névé line is still more plainly seen. There is thus evidence that a wave, or impulse, derived from an increased precipitation over the névé region, travels the length of the glacier and gives rise to a halt, or an advance, of the front; followed by a depression which permits of a retreat. Such a depression appears to have been at the edge of the névé line in 1887 or 8, while the glacier about the lower extremity was experiencing the effect of a previous impulse. The retreat of the glacier was greatest between 1890 and 1900, and if we assume that it culminated at about the middle of the decade, it required about 8 or 9 years for this trough of the wave to reach the nose, or at the average rate of 800 to 850 feet per annum. Since in 1905 the appearance of the sky-line along the névé corresponds so nearly with that seen in 1888, we may assume that the crest of the wave was in this position at a date only a little later than the mean of the two. This would bring it to about 1898 or 9, when it was especially noted by the Messrs. Vaux. The gradual reduction in the rate of retreat observed during the past three seasons would indicate that this impulse is making itself felt about the nose and that either a halt, or an advance, is about to be inaugurated. If we are correct in the inference that the névé line was marked by a trough, or low stage in the height of the ice, about 1887 or 8 and that a return to this condition has been reached about 1905 or 6 with a crest, or high-stage condition of the ice between, an interesting relation is at once established with Brückner's climatic cycle (page 16). The time between the appearance of these troughs for the passage of one-half of the wave is 18 years, and we may venture to predict that the present relative depression will be followed by the passage of another crest requiring about the same number of years. The nose has been in retreat from 1888 to 1906, some 18 years, and we should expect another period of halt or advance to soon set in. Such a condition was to be anticipated from the marked reduction in the rate of retreat from 1902 to 1905, but the very remarkable recession of 84 feet determined by the Messrs. Vaux for the year 1905–1906, leaves the matter in doubt.

The relation of the glacial movements to the precipitation cycles becomes a matter of much interest and here, as above, with our meager data, we can only point out possibilities, which will either stand or fall, when the next half-century's observations have been collected. From our available meteorological records there was a deficiency of precipitation over the mountains from 1885 to 1896; how much before 1885 this condition existed we have no means of knowing. Since 1897 there seems to have been an excess over the normal amount, but it was at this time that the crest of the wave made its appearance at the névé line. Then instead of continuing to increase, as we might expect, it gave way to a trough. The inference is, and it is only an *inference*, that this wave represents the gush of ice from the collecting basin due to the excess deposited during the phase of the cycle which antedated 1885, and probably to be correlated with the excess in the Rockies, as recorded so strikingly in the evidence of higher lake levels, described by Dawson (page 17). The approaching trough shown about the névé line in 1905 must then be ascribed to diminished precipitation received over the collecting region from 1885 to 1896, being then 9 years delayed from the close of the phase which gave rise to it. The crest of the wave from the basin was delayed some 17 to 18 years from the close of the preceding phase. In a paper read before the International Geographic Congress, at its Washington meeting (*Proceedings*, 1904, p. 487), Doctor Reid gave a discussion of "reservoir lag," in which he demonstrates mathematically that the thickening of ice in the collecting basin does not keep pace with the variation in precipitation, but lags behind it. In the case of large glaciers this lag amounts to about one-fourth of the period of the variation, and the ice in the basin should attain its maximum thickness, only about the time that the annual supply has settled back to the normal amount and is ready to diminish. After the maximum ice thickness has been attained toward the center, time is still required for the impulse to reach its maximum at the crest of the basin, the amount of which will differ with the local conditions. In this way we may account for the delay in the arrival of the crest at the névé line in the years 1897–9.

9. Former Activity.

a. Rock scorings. The former work of the glacier is shown in great beauty and variety upon the mass of bedrock now being gradually uncovered near the nose. The hard rock features of Pleistocene glaciation are all here for study by those interested, many of them indicating the direction of ice movement and hence of practical value in the field.[1] Excellent examples of the so-called roches moutonnées occur, groups of which in the distance often resemble crouching sheep (plate XXXIV, figure 3). In the specimen figured, the ice moved from right to left across this projection of bedrock, the up-stream, or stoss side being rounded and smoothed, while the down-stream, or lee side, was affected slightly, or not at all. Portions of the rock were polished, as the ice was rubbed vigorously across, and where the ice held rock fragments against it, systems of approximately parallel scratches were produced, some so fine that they must have been made by sand grains. At the last stage of the disappearance of the ice from this particular roche moutonnée, a small clump of rock fragments was gently dropped upon the upper surface in insecure position. An inspection of this and the adjoining rock in the figure, shows a system of parallel joints, dipping down-stream at a steep angle. From the lee side of the central roche moutonnée it is apparent that an entire block was pried loose by the ice and that a little more vigorous action at the joint, just beginning to open, would have removed bodily nearly the entire block. This action is known as "plucking," already described in connection with the Yoho (page 79), by which the work done in a few days may exceed the erosion of years. Places may be seen upon the surface where a rock engaged in producing a shallow groove has made a succession of jumps and given rise to a series of short parallel curves, more or less closely placed, with their concavities directed down-stream. These are the "chatter-marks," the production of which may be illustrated by pushing a dry finger over a polished surface. In other cases rocks embedded in the under side of the ice have been suddenly brought into action, producing a crescentic gouge, with its convexity directed in the direction of flow.[2] The bedrock here being a schistose conglomerate with rather coarse, hard masses embedded in a softer matrix, there have been produced the "knob and tail," or "knob and trail" phenomena, so useful often in determining the direction of ice flow in the case of Pleistocene glaciers. In one case examined there appeared a dark colored knob of harder material, which the ice was unable to cut away as rapidly as the surrounding schist. The projecting knob had partially protected the softer material in its lee,

[1] A most valuable paper by Chamberlin upon the effect of ice upon rock will be found in the *Seventh Annual Report of the Director of the U. S. Geol. Surv*., 1888, page 155.

[2] See paper by Gilbert read before the Cordilleran Section of the Geological Society of America at its 1905 winter meeting. "Crescentic Gouges on Glaciated Surfaces," *Bulletin Geol. Soc. of Amer.*, vol. 17, pp. 303–314.

forming an elongated tail, or trail, extending from the knob in the direction of ice motion. In some cases a small quartz vein cuts across the surface in such a way as to protect in its lee a strip of the softer rock. In front of the knobs there is cut out, as a rule, a frontal groove lying at the base and curving around laterally into two others, one upon either side, forming the lateral grooves. In places where the ice acted with greater vigor, owing to the concentration of its action, or where differences existed in the structure, or hardness, of the rock there were cut out basins and U-shaped troughs, representing, in miniature, lake basins and glaciated valleys. One basin, with perfectly smoothed sides and bottom, had a length of 15 feet, a breadth of 6 feet, and a depth of 6 to 8 inches below its lower rim. The greatest depth was located one-third of its length from the upper end, indicating where the gouging action had been greatest. One of the troughs was 11 to 12 feet across and 4 to 5 feet in depth.

b. Bear-den moraines. Some 800 to 900 feet below the terminal moraine of 1887, or about 1,400 feet from the nose of the ice in 1904, there occurs a moraine of the same general type as that described under this head in connection with the Victoria. This consists of very massive blocks of quartzite, arranged in a north to south ridge across the valley, having a breadth of about 400 feet and a height above the general valley floor of 20 to 40 feet. The largest block observed was measured by Messrs. Moseley and Todd and its dimensions, above ground, were found to be about 107.5 by 28 by 11 feet, from which it was estimated to weigh about 2,000 tons. A portion of this ridge is seen in plate XXXVI, figure 1, taken from one of the blocks of the moraine itself, looking toward the glacier up the valley. The blocks are blackened with lichens, more or less moss-covered, and carry enough soil to support considerable vegetation of a larger size. A spruce growing upon the moraine had been cut and with a circumference of 128 centimeters gave 243 rings of growth. A hemlock, also upon the moraine, with a circumference of 320 centimeters (50 centimeters from the base), was calculated to be 447 years of age. This estimate was based upon the average breadth of the annual rings of growth measured in the Illecillewaet and adjoining Asulkan valleys. This average breadth was found to be 1.140 millimeters, as compared with 0.884 millimeter in the Lake Louise Valley.

From the outer edge of this moraine, 1,500 feet down the valley measured along the stream, there begins another similar but larger moraine of the same type. Starting from the spur of Glacier Crest which separates the Illecillewaet and Asulkan valleys, the ridge swings out across the valley bearing N. 8° W., and then swings around to N. 15° W. It is 200 to 300 feet across and some 50 to 60 feet above the valley floor, somewhat steeper toward the glacier. The blocks are very coarse quartzites and schists, blackened with lichens, and presenting angular outlines. The largest block noted was estimated to weigh 1,250 tons. The usual filling of a moraine, gravel, sand, and clay, is practically absent. Upon the eastern side, for a portion of its length, it is covered by a mass of broken tree trunks which were swept from the side of Mt. Eagle by an avalanche (plate XXXVII, figure 1) some decades ago. Enough soil has accumulated about the rocks

FIG. 1.—"Bear-den moraine" made conjointly by the Illecillewaet and Asulkan Glaciers. Strewn with timber avalanched from the right-hand mountain slope.

FIG. 2.—Illecillewaet Glacier in 1897. Photographed by Notman & Son, Montreal. Compare with plate XXXVI.

Map of Asulkan Glacier, Asulkan Valley, Selkirk System. Surveyed and drawn by W. H. Sherzer, August, 1904 Field assistants De Forrest Ross and Frederick Larmour. Elevations from A. O. Wheeler.

to support a growth of raspberries, blueberries, etc., and also a few spruce 8 to 12 inches in diameter. The bulk of the material lies to the west of the glacial brook and was derived from the eastern side of Glacier Crest and Mt. Lookout, the cliffs of which have a northwest-southeast trend. The shape of the moraine and the way in which the blocks have been deposited indicate, as noted by Prof. Penck at the time of his visit, that the moraine was built conjointly by the former Illecillewaet and Asulkan glaciers. The blocks contributed by the Asulkan came from the western side of Glacier Crest and the Asulkan Ridge, and are much less in amount than those derived from the eastern side and transported by the Illecillewaet. The largest tree found growing inside of this moraine was calculated to have been 520 years old when it died and from the condition of its wood and bark to have been dead about 30 years.

CHAPTER VII.

ASULKAN GLACIER.

1. General Characteristics.

Lying at the head of the Asulkan Valley, upon the opposite side of Glacier Crest from the Illecillewaet Glacier (see plates xxxii and xxxiii), is located the Asulkan Glacier. Its broad expanse of snowfield extends in a semicircle from Asulkan Ridge, past Leda, Pollux, and Castor to the northern extremity of the Dome, faces to the northward, and under the sunlight is of dazzling whiteness. The name is of Cree Indian origin and is generally said to mean "goat," but I am assured that it really means "bridge." The nose of the glacier lies about three miles from the station, reached by a picturesque and easy trail, except in the upper part, where the trail becomes steep. The glacier itself may be safely visited and studied without a guide, but no one should venture upon the névé unattended, as it is very treacherously crevassed. This glacier is the smallest and the most southern and western of the series here reported upon, its nose lying in longitude 117° 28′, west and latitude 51° 13′, north.

The glacier consists of three streams, two of which are closely united and the third separated from the other two except in the névé region where they are all united. The length of this third stream, measured from the Asulkan Pass, is about two miles, of which the first mile is névé and the lower mile is ordinarily free from snow during the summer season (plate xxxix, figure 1). The breadth of the dissipator is about 1,800 feet in the upper part, but about the middle of its course it makes an abrupt bend from the north to the northeast and tapers gradually to a sharp nose. The eastern margin curves around gradually to the nose, while the western side is curiously straight, cutting diagonally across what appears to be the natural course of the glacier. There seems no apparent reason for this abrupt bend in the glacier and for the remarkably straight western margin of the ice, but the explanation will appear in what follows. This peculiar contouring of this stream gives it the general form of a bear's paw—a *polar* bear

—in which the straight margin represents the sole. From near the heel of this foot there extends southward a long, slender ridge of glaciated rock, carrying more or less morainic matter, which separates this eastern ice stream from the double ice mass immediately to the west (plate XXXIX, figure 1). Judging from the line of crevasses and faulting across the névé, there lies another similar ridge, parallel with the first and about one-quarter mile to one-half mile to the west, which separates this mass into two streams, each having its own separate nose, as shown upon the map. This ridge is apparently the continuation of the line of bedrock exposed along the right-hand margin of the westernmost ice stream. The névé line upon this glacier is about 7,000 feet above sea-level and the main portion of the névé lies between this altitude and 8,000 feet. From the Asulkan Pass (7,710 feet) to the nose of the easternmost stream the descent is 2,110 feet, or at the rate of 1,055 feet to the mile. The altitude of the nose is 5,600 feet, or some 800 feet higher than that of the Illecillewaet, due apparently to the smaller volume of ice in the Asulkan and its dissipation at three separate points. The altitudes of the two higher noses to the west are about 6,000 feet, or the same as the Victoria. So far as may be judged from the crevasses and faultings, the ice responds fully to the irregularities in its bed which indicates that it is relatively thin. The surface slope of the western and middle streams is very steep; that of the easternmost, or main, stream is much more gentle, amounting in places to not more than 6°. Toward the nose the inclination becomes 25° and then drops off to but a few degrees, so that it may be readily ascended. Upon either side of the stream the marginal slopes are steep for a few hundred feet back from the nose.

2. Piedmont Characteristics.

If the reader has covered Chapter IV of this report he will have recognized already the piedmont character of the Asulkan, which consists of three commensal streams. The glacier is of peculiar interest because it is an illustration of a piedmont glacier in its senile condition. It has reached its second childhood and now illustrates the disintegration of a piedmont glacier into the component streams, the union of which in its youth gave rise to the glacier itself. Every glacier of this type begins with the independent development of a system of Alpine glaciers, coördinate in importance, which coalesce laterally into a single ice mass. The length of the glacier is determined by the length of the separate streams composing it and its breadth by the number of streams and their combined breadth. In the final stages of dissolution, which must come sooner or later in its life history, the piedmont glacier shrivels back into the original Alpine components. The eastern tributary has already separated sufficiently so that it may be regarded as an independent glacier. The other two have separated for a distance of about one-fourth of a mile, but the separation will not be complete until the ridge of rock above noted has appeared at the surface of the ice. The middle stream covered the ridge of rock, now exposed between it and the eastern stream, and sent its nose down the valley as far as the drainage brook

FIG. 1.—General view of Asulkan Glacier in 1902. Copyrighted, 1902, by the Detroit Photographic Co.

FIG. 2.—The Asulkan glaciers and snowfields from Avalanche Mt. (elevation 9,387 feet), showing a decadent piedmont glacier. Photographed in 1901 by Arthur O. Wheeler.

shown upon the map. There it formed a series of terminal moraines upon its eastern side, the eastern component standing at about the same level and forming a similar series. The sudden bend noted in the eastern component, one-half mile back from the nose, resulted from its pressure against the side of the middle stream which it was unable to force aside. Conjointly they formed a straight medial moraine from the bend to the nose. Upon the more rapid retreat of the middle stream and its disappearance from this part of its bed, this moraine became the left lateral of the easternmost stream (plate XXXIX, figure 1), and was of such a massive character that it has continued to deflect the ice from its natural course.

In plate XXXIX, figure 1, we have shown nearly the entire eastern and middle streams of the Asulkan, and a portion of the névé of the western. A distant view of the entire glacier is given in plate XXXIX, figure 2, taken by Wheeler from the summit of Avalanche Peak (9,387 feet) in 1901. The Dome may be recognized from its contour and from it there is seen to be a broad ridge extending valleyward and marking the western limit of the present Asulkan Glacier. To the right of this ridge, along the eastern slopes of Mts. Afton (8,423 feet) and Abbott (7,710 feet), four marked depressions occur, each containing small-sized glaciers. The contour of the rocky slopes separating these amphitheaters, or *cirques*, as they are termed, proves that at an earlier stage of glaciation these streams coalesced laterally and united with the present Asulkan, forming a grand, hanging, piedmont glacier, extending from the Asulkan Ridge to Mt. Abbott with at least nine or ten main commensals. Previous to this stage they had united with others from the head and opposite side of the valley into a grand Alpine glacier, which became a tributary of the ancient Illecillewaet trunk glacier in Pleistocene time.

3. Nourishment.

The névé field of the present Asulkan is arranged in the form of a semicircular belt, extending from the Asulkan Ridge upon the east around to the Dome upon the west, having a length of about three and a half miles and an average breadth of perhaps three-fourths of a mile. The area of this field is somewhere between two and a half and three square miles, or less than half that of the Illecillewaet névé field. The amount of precipitation over this field cannot be essentially different from that given for the neighboring glacier (page 82). From an elevation of about 7,000 feet the névé snows reach up to the crests of the bounding ridges, in many places, attaining an elevation of 9,000 feet. It is possible to pick out, in a general way, the névé fields by which the separate ice streams are nourished. The eastern stream receives its supply from Asulkan Ridge (9,100 feet) and from the Pass (7,710 feet), the former moving westward down the oblique slope and delivering its supply of ice and subglacial débris to the right side of the main stream flowing from the Pass. A still less amount is received from the opposite side from the snow that accumulates upon the northern slope of the unnamed peak (8,700 feet +) lying to the east of Leda. The Pass and upper névé are reached by means of the right lateral moraine. Judging from the course of the transverse crevasses, which lie at right angles to the main direction of flow, the névé that accumulates between this minor peak and Leda (9,133 feet) moves northward and nourishes the middle ice stream. The oblique course is taken probably because of the continuation southward of the ridge of rock previously noted as separating the middle and eastern streams. The presence of a similar ridge beneath the ice deflects the névé snow and ice from the northern slopes of Castor (9,108 feet) and Pollux (9,176 feet), to which is added that from the Dome (9,029 feet), and thus is obtained the supply for the double-nosed western ice stream. The middle stream is least well supplied at the present time with ice from the névé field and has receded farthest. It seems very probable that when the ice was thicker over the névé there was relatively less of it deflected to the western stream by the subglacial ridge and this fact permitted the middle stream to maintain the same length as the now better nourished eastern. The superficial layers from Castor and Pollux could move directly across those which the configuration of the bed deflected northward, but as the general elevation of the névé was lowered a relatively greater and greater percentage of ice was deflected to the western stream and the nose of the middle stream retreated steadily some 2,200 feet up the slope, to an elevation at present 400 feet higher than the nose of the eastern stream. Were the ice of all three streams now concentrated into a single one it is probable that the nose would attain as low an altitude as that of the Illecillewaet.

4. Moraines.

Owing to the absence of high, overtowering cliffs, such as we find in the case of the Wenkchemna and Victoria glaciers, the névé fields of the Asulkan receive very little rock débris over their surfaces. In consequence, the ice itself, except along the margins, is quite free from rock fragments. As in the case of the neighboring Illecillewaet collecting basin, conditions are favorable for receiving wind-blown dust from peaks and ridges towering above the snow. This dust is distributed somewhat evenly over the snow and, when concentrated by melting, gives rise to the stratification and imparts a soiled appearance to the ice about the lower margins.

The right lateral moraine of the eastern ice stream makes its appearance just east of the nose and south of the stream from Asulkan Ridge. It rises at once into a conspicuous, sharp-crested ridge, extending south-southwestward, and bending abruptly to the south-southeast, attaining the length of a mile before it dips under the névé snow. The lower portion of the moraine seems entirely free from ice, the outer slope carrying fir and spruce 50 to 60 years of age. The inner slope is more steep and has younger vegetation, indicating that the ice has within a few decades withdrawn from the moraine. The crest rises to a height of 60 to 70 feet above the valley floor upon which the glacier rests. The rocks consist largely of bruised and rounded quartzites and schists, which in the upper part are embedded in a matrix of glacial clay. This material appears to come from beneath the glacier that covers the western slope of Asulkan Ridge,

FIG. 1.—Left Asulkan moraine shedding its rocky covering and exposing the ice core.

FIG. 2.—Débris-covered nose of Asulkan Glacier, August, 1904. Glacier had been advancing for some three or four years.

by which it is delivered to the main stream from the Pass, as previously noted, upon a level with its surface. This névé-covered glacier sustains the same relation to the Asulkan that the Collie and Gordon glaciers do to the Yoho. Between the crest of the moraine and the glacier there intervenes a steep boulder slope, about 300 feet broad in the lower portion near the nose, but narrowing gradually for a half-mile, when the moraine and ice meet. Opposite the nose, upon the eastern side there is an outcrop of a silvery schist, with its strata upon edge, which has been glaciated and plucked.

The development of the left lateral of the eastern stream from a former medial has already been described and its very straight course obliquely across the valley been accounted for. Originally, this moraine may have been largely subglacial, or englacial, the material being derived from the basal layers of the ice. The slope of the valley floor is northward, while this lower half-mile of the moraine bears northeastward. After making the very abrupt bend noted, the moraine continues for a quarter-mile farther, resting upon the rocky ridge of quartzite and a greenish schist. This ridge raises the base of the middle stream above the present surface of this portion of the eastern stream. The moraine consists very largely of ground moraine, supplied apparently in large part by the middle ice stream, but instead of clay the filling is a glacial sand. The finer material may have been removed by currents too gentle to transport this sand. The inner slope of the moraine is steep, the outer is more gentle down to the drainage brook from the middle nose. The crest of the moraine rises 125 to 150 feet above the floor of this valley. About one-quarter mile back from the nose this moraine begins to shed its cover of rock débris, revealing in a most interesting manner the real structure of such a moraine. From this point up the valley the moraine is a typical, sharp-crested structure (plate XXXIX, figure 1), but here the débris has begun to slip to either side, forming a double ridge with a continuous ice crest between. Plate XL, figure 1, gives a view of this exposed ice core, looking up the glacier along the inner side. The highest portion of the ice ridge attains a height of 25 to 30 feet, which is being rapidly acted upon by the sun in midsummer. Where it has been longest exposed the ice has melted below the general level of the glacier, forming a depression with a ridge of rock débris upon either side, the outermost one being quite prominent. Into the depression the material from either side has begun to roll and slide, thus protecting the ice at the bottom of the depression from the sun. Had the thickness of the ice proved sufficient, in time the rock débris would have gotten back, in large part, into the depression, allowing the ice to melt upon either side and starting again the formation of a single-crested, typical moraine. Thus it appears that moraines may, under certain circumstances, pass through the same series of stages as those described for surface lakelets upon page 57 of this report.

About the eastern nose there has been pushed up a ridge of ground moraine, from 12 to 15 feet high, into which the ice nose plunges and buries itself. Upon this ridge minor ridges, but a foot or two in height, also occur, as seen in plate XL, figure 2. At times the nose is so deeply buried that it is difficult to find it for purposes of measurement. When the middle stream stood at this lower level, the two built a series of three or four latero-terminal moraines which curve gently down the valley from the lower ends of the laterals. The inner terminal of the middle stream has the appearance of age, compared with the others lying just east, and is being covered slowly with low shrubs and evergreens. From this difference in age one would infer that the ridges of the series, lying to the east, had been built by the eastern stream alone. The nose of the middle stream, especially upon its eastern side, rests largely upon bedrock, more or less strewn with rock fragments. The rock here, as elsewhere about the glacier, consists of quartzite and schist, plucked and glaciated. Along its left side, back as far as it has become separated from its neighbor, it has built a sharp-crested, lateral moraine, which in the lower half is double, curving gently down the bouldery slope. The inner slope is steep, the outer long and more gentle. The boulders are rounded and bruised but only occasionally well glaciated. The double western nose is similar to the middle, in that it is steep, perched high up on the slope, has bedrock exposed upon its eastern side, while upon the left it has built a short, sharp lateral extending up to the névé. In front of the western and middle streams there has been uncovered a steep slope of bouldery ground moraine so recently that trees have not been able yet to get anything more than a start.

5. Crevasses.

Owing to the irregularities in its bed, the steep slopes, and the apparent thinness of the ice, the Asulkan streams are badly crevassed and faulted. The névé fields of the western and middle streams cannot be traversed with any degree of safety, while that of the eastern calls for the greatest skill in locating the snow-covered death-traps (plate XLI). The crevasses in the névé portions are mainly of the transverse type, caused by the rapid movement of the ice over an irregular, steep slope. They stand approximately at right angles to the direction of motion and furnish a clue as to the general movement of various portions of the névé field. Just below the névé line the eastern stream encounters, in its central portion, an obstruction by which the ice is shattered in every direction, but mainly transversely (plate XXXIX, figure 1). The descent is not rapid enough to constitute a cascade and the blocks, at first angular, become sharpened by melting into seracs but retain their vertical position until melted away at the base of the slope. The development of these seracs is well shown in plate XLII, figure 1. The ice exposed portion, or dissipator, of this stream shows numerous marginal crevasses along either side of its course, those upon the eastern side, in the lower portion, extending beyond the central axis. Those upon the western side are not so strongly developed. It is upon the middle stream that the dirt band crevasses occur figured in connection with the discussion of this subject (plate XVII, figure 1). The slope, however, is too steep for their formation and preservation.

FIG. 1.—Stratification of Asulkan Glacier. The dates are added upon the supposition that the strata represent seasonal deposition. Copyrighted, 1902, by the Detroit Photographic Co.

FIG. 2.—General view of Asulkan Glacier in 1898. Reproduced through courtesy of the Messrs. Vaux. Compare with plate XXXIX, figure 1.

6. Ice Structure.

The névé-covered portion of the ice acquires a very perfect stratification as the result of wind distributed dust and periodic melting over the surface. This structure is beautifully shown in the crevasse walls and the faces of the numerous faults in the ice. In the photograph of the Detroit Publishing Co., reproduced in plate XLI, the successive layers, with the minor stratification seams, are clearly shown. The correspondence of the strata upon opposite sides of the crevasse shows that there had been no faulting. From his heel to the crown of his hat this guide pictured is about six feet in length and, by comparison, we ascertain that the strata shown range from three to twelve feet in thickness. The picture was taken during the summer of 1902, and in looking at the uppermost stratum it is forced upon one's belief that this represents the compacted snow that accumulated over this spot during the season of 1901–2. Part of this snow was precipitated directly, part of it may have been drifted by wind action. It may have lost some by wind action, as well, during the season of accumulation. It has been compacted by melting, pressure, and occasional rain into a fine granular ice. If we are right in supposing that this stratum represents the accumulation during the season of 1901–2, minus the loss by the combined agencies, then the stratum upon which it rests must have accumulated during the season of 1900–1. Passing down the side of the crevasse we may thus assign dates to the successive strata, finding that they reach back to the season of 1895–6. It is especially interesting to note that the deposits supposed to have been laid down between the summer of 1898 and that of 1902 average considerably thicker than those between the summers of 1895 and 1898, since this dividing date falls very near the supposed date of the beginning of the phase of increased precipitation in this region. It is further to be noted that the stratum marked 1898–9 is the thickest of the series. It is very unfortunate that our precipitation data are not fuller for the locality. In order to serve the present purpose in establishing a relationship between the amount of precipitation and the thickness of the strata in the névé, a combination should be made of the last three months of the year with the first nine of the following year. This would unite practically all of the snowfall and the rain and melting water of the following summer, as it is combined in the stratum itself. In a paper upon the Canadian Pacific Railway, from Laggan to Revelstoke,[1] Mr. William Vaux gives the average snowfall for Glacier House from 1895 to 1898 as 31 feet, based upon records kept by the station agent, this being but 83 per cent. of the normal. From October, 1898, to May, 1899, inclusive, the snowfall alone amounted to 43 feet 8½ inches, being 17 per cent. above the normal. The records are lacking up to 1902, for which year the Meteorological Service reports 13.88 inches of rain and 347 inches of snow, or a total equivalent of 40½ feet in snow, or 14 per cent. below the normal. By referring to plate XLI it will be seen that the stratum assigned to the year 1898–1899 is the heaviest of the series while that for 1901–1902 is light. From 1895 to 1898 the strata are

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[1] *Proceedings* of the Engineers' Club of Philadelphia, vol. XVII, 1900, p. 73.

thin, corresponding to the average lighter snowfall above reported for these years.

A still further confirmation of the conclusion reached above, that from the middle of the year 1898 there has been a marked increase in the snowfall, is furnished by the notes and photographs of the Messrs. Vaux, to be noted later. Their photograph of 1898 shows a large amount of rock exposed along the slopes of Leda, Pollux, and Castor, as well as between the eastern and middle ice streams. In 1899 they note that the névé line is lower and the *hanging glaciers* are much more active, giving rise to frequent avalanches, which were very infrequent in 1898. When their photograph of 1898, reproduced here as plate XLI, figure 2, is compared with that of the Detroit Publishing Co., taken in 1902 (plate XXXIX, figure 1), the increase in the amount of névé is striking, the presence of the bergschrunds, in areas that were bare rock, indicating that glaciers had formed in the meantime and that there is not simply a covering of loose snow, such as might fall in a night. In looking over the broad snow expanse one does not think of there being *hanging* glaciers upon the slopes of Castor and Pollux, as they seem to blend with and be an integral part of the general névé field. In 1898 they were separated sufficiently so that it was natural to think of them as being detached. In two weeks of August, camping in plain sight of the region, in 1904 and 1905, the writer does not remember to have seen or heard a single avalanche from this quarter. They were frequent in the summer of 1899, and, presumably, continued so until the space between the lower névé and the upper became so filled in as to prevent further slides. From all the evidence obtainable it seems most probable that the major stratification planes in the Asulkan névé represent the breaks between the successive year's snowfall, and that a phase of deficient precipitation closed in this region about the middle of the year 1898, since which time the average annual precipitation has been in excess of the normal.

The disturbance of the ice noted upon the eastern stream does not destroy the stratification, since it extends only part way across the stream and is not intense. The strata are, however, more or less tilted and distorted. The lower stratum is wedge-shaped, having apparently lost from its basal portion by subglacial melting. The blue bands in this stratum are not parallel with its upper surface, but cut it at angles of about 13° to 14°, being more nearly parallel with the valley floor. In the stratum just above, the blue bands and stratification planes were conformable. In general, the blue bands were found to be regularly developed, quite in contrast with the stratification. The dirt stripes showed well over the surface and margins of the eastern stream, some excessively thin ones being observed and previously noted (page 54). About the nose, upon the walls of some of the longitudinal crevasses, the blue bands were found to dip back into the glacier at angles of 11° to 28°. About the eastern side they were found to dip downwards and inwards, nine observations giving an average of 46°, with a range from 36° to 57°. The granules about the nose are small, compared with those seen in the larger glaciers, and will average less than a half-inch in diameter.

7. Drainage.

Owing to the crevassed condition of the ice the surface streams are small, dropping into the glacier, or to the bottom, before they can develop any size. Over the névé area the water resulting from melting, or from rains, is at once absorbed. Over the ice exposed portions, during hours of melting, small rills and surface brooks come into existence, carrying water with a temperature of 32°. No lakelets were noted upon the glaciers, or about the margins, but upon the col, lying between Castor and the Dome, Mr. Wheeler found a lakelet of sapphire blue water. Under ordinary conditions there is practically no marginal drainage. In 1904, back some 800 feet from the nose of the eastern ice stream, a small flow was visible for a short distance. From each of the three noses there issue two to three drainage brooks, those from the eastern uniting with one another and with the drainage from Asulkan Ridge, after which is received the central flow from the middle portion of the glacier. That from the western commensal, along with the drainage from the hanging glaciers lying farther to the west, cascades into the Asulkan Valley, forming the "Seven Waterfalls." The flow from the eastern nose is the strongest and carries the most sediment, considerably more than the Illecillewaet. It fluctuates in volume during the day, reaching its maximum in the late afternoon, or evening, and being lowest in the early morning. The combined drainage from the middle and eastern portions of the glacier, along with that received from the Asulkan Ridge to the eastward, has cut a gorge 30 to 40 feet deep through the soft schist. This has the appearance of having been done since the withdrawal of the ice, but it may have been started by a subglacial stream. Under high velocity and charged with sharp, glacial sediment the cutting power of water must be rapid upon a soft schist. Its action upon quartzite boulders is well seen in the bed of the brook from Asulkan Ridge.

During the last week in August in 1904 and 1905, the average of 28 observations upon the temperature of the water from the eastern nose was 32.42° F., the range being from 32.0° to 33.0°. Two observations upon the water from the middle nose, upon leaving the ice, averaged 33.0°, while from the third nose it was 32.8°. Before receiving the middle drainage the temperature of the brook was 36.9° and after the two had united just above the schist cut the temperature was 37.8°. Passing down the valley some two miles, and receiving drainage from either slope, the temperature at the bridge across the Asulkan Creek averaged 42.6°. The water is here turbid but assuming more or less of a greenish cast. The stream from the Asulkan Ridge before receiving the flow from the glacier was found to average 36.5° (20 observations). These observations seemed to indicate that the maximum temperature was attained between 11:00 A.M., and 1:00 P.M., and that as the volume of water increased as the day advanced the temperature gradually fell. This is brought out in the table here given.

TEMPERATURES OF STREAM FROM ASULKAN RIDGE.

1904.			1905.		
Aug. 30.	7:10 A.M.	35.2°	Aug. 28.	6:00 A.M.	35.8°
Aug. 26.	7:15 A.M.	35.6°	Aug. 28.	7:00 A.M.	36.1°
Aug. 27.	9:10 A.M.	36.9°	Aug. 29.	9:00 A.M.	37.0°
Aug. 31.	10:15 A.M.	36.3°	Aug. 27.	11:00 A.M.	38.7°
Aug. 27.	1:10 P.M.	37.8°	Aug. 27.	2:00 P.M.	37.9°
Aug. 25.	6:05 P.M.	36.5°	Aug. 27.	3:10 P.M.	37.4°
Aug. 28.	6:15 P.M.	35.6°	Aug. 27.	4:00 P.M.	37.0°
Aug. 25.	6:50 P.M.	35.2°	Aug. 27.	5:00 P.M.	36.7°
			Aug. 27.	6:00 P.M.	36.3°
			Aug. 27.	7:00 P.M.	36.0°
			Aug. 27.	8:00 P.M.	36.0°

8. Frontal Changes.

Points of reference for the study of the frontal behavior of the lower Asulkan nose were established August 12, 1899, by the Messrs. Vaux and observations and photographs have been repeatedly made by them since. At that time they made an unsuccessful search for reference blocks previously marked by H. W. Topham. One year previously (August 23, 1898) they had visited the glacier and obtained a photograph from their "test rock," which was published, along with a brief description of the glacier, in the paper previously referred to.[1] A comparison of their test picture of 1898 (plate XLI, figure 2) with that of 1899 showed a slight shrinkage in the height and a slight increase in the breadth, "while the position of the tongue had not changed to an appreciable extent." The ice fall appeared to be less and they note that the névé line was lower, the glaciers upon the slopes of Castor and Pollux more active, giving rise to a number of avalanches, which seemed very infrequent in 1898. In marking the position of the tongue at the time of their visit in 1899 three rocks were selected in a line with the nose, the magnetic bearing of which was N. 85°35′ E. One rock was located upon the small, left lateral moraine, a second just below and to the right of the nose, while the third lay upon the inner side of the higher right lateral. In 1900 the Messrs. Vaux observed a retreat of 24 feet and "a marked shrinkage in every dimension." From 1900 to 1901 these observers reported an advance of 4 feet and for the two years 1901 to 1903 an additional advance of 36 feet.[2]

This glacier was first visited by the writer September 17, 1903, at which time it was found that the nose of the glacier lay 13½ feet beyond the Vaux line, which was readily located by the two well marked end rocks. This would indicate that the nose had retreated 2½ feet between the date of Vaux's measurement in 1903 and September 17 of the same year. The stone that had been marked near the nose had been pushed forward some 14 to 15 feet, turned on end and was about to topple over. Upon August 27, 1904, the nose lay 12½ feet beyond the line, indicating practically no change, when allowance is made for difference in

[1] "Some Observations on the Illecellewaet and Asulkan Glaciers of British Columbia," *Proceedings of the Acad. of Sci. of Phil.*, 1899, p. 121.

[2] "Variations of Glaciers," H. F. Reid, *Jour. of Geol.*, vol. XIII, 1905, p. 316.

dates of observation. Exactly one year later (August 27, 1905) the nose had made a retreat of 34 feet from the position held in 1904, standing now 21½ feet back from the reference line established in 1899. The nose consisted at this time of a thin slab of ice, sloping to the west and coated with fine débris. A relatively small amount of melting would cause a further recession of 30 to 35 feet. The ice in the left lateral moraine was found to extend four feet beyond the reference line and 25½ feet beyond the nose. Owing to the rock cover it could not be ascertained how much farther the morainic ice core extended. The movements of this nose may be summarized as follows:

Changes in the Nose of the Asulkan Glacier.

(Eastern Ice Stream.)

1898–1899.	"Practically no change."
1899–1900.	Recession of 24 feet.
1900–1901.	Advance of 4 feet.
1901–1903.	Average advance of 18 feet.
1903–1904.	Retreat of 1 foot.
1904–1905.	Retreat of 34 feet.
1905–1906.	No change.

9. Former Activity.

a. Development and decadence. At a much earlier stage, presumably in Pleistocene time, the combined snows of the Asulkan Valley united into a great Alpine glacier, the ancient Asulkan, which was a tributary of the ancient Illecillewaet, and this, in turn, a tributary of the great trunk glacier that flowed southward in the Columbia Valley, to the west of the Selkirks. With the diminution of snowfall, and possibly also an amelioration of the climate, the glaciers disappeared from the main valleys and withdrew into the tributary valleys and alongside the steep, higher slopes. An Alpine glacier occupied the Asulkan Valley from the Pass to where the valley joins the Illecillewaet, some four miles in length, which was in part nourished by a hanging, piedmont glacier extending from the Pass to Mt. Abbott. This glacier sustained, during this stage, the same relation to the Asulkan lying in the valley, that the hanging Victoria sustains to the lower ice stream. The effect of these great ice masses upon the valley floor and sides was similar to that already discussed for the Victoria and Yoho glaciers (pages 61 and 80).

b. Bear-den moraines. Just before the complete and final separation of the Asulkan from the Illecillewaet, the Asulkan became loaded with very coarse, angular rock fragments, and only a minimum of fine material. This was at the same time that the Illecillewaet was similarly laden and, conjointly, they deposited the massive bear-den moraine described upon page 96. The most of its material was deposited upon its right, showing that it must have been received from the western side of Glacier Crest and Mt. Lookout. The amount carried was notably less than that brought down by its neighbor lying to the east of the Crest. The ridges about the head of the valley and along the western side were largely under snow and ice and could supply no such débris. After this load of rock had been deposited the Asulkan began to retreat, withdrawing a distance of 3,500 feet up the Asulkan Valley. The front now halted and there was built a moraine of the ordinary type across the valley, consisting of fine and coarse material, intermingled with but few coarse blocks. From this we conclude that the glacier was, at this time, carrying the ordinary kind of load. The retreat was resumed and in the meantime the glacier became a second time laden with coarse fragments of the adjoining cliffs. At a distance of about 1,000 feet from the previously formed moraine these blocks began to be deposited and were dropped over a distance of some 500 to 600 feet, not so concentrated or imposing as the outer bear-den moraine. For the next 1,500 feet these blocks were scattered along the valley, implying that the supply over the surface had not been sufficient to bring about a halt. The retreat continued towards the head of the valley and at a distance of 2,000 feet farther a halt occurred and a moraine of the ordinary type was again built, with the usual quota of fine and coarse material. From the time then that the Asulkan was about to separate from the Illecillewaet it became twice loaded with coarse, angular fragments of quartzite, building a moraine of the bear-den type. In the interval it carried material of the ordinary kind found upon and within the ice and built a moraine of the ordinary type. Subsequently to the formation of the second, straggling, bear-den moraine, it has been carrying and depositing the usual class of material. It differs from the Victoria in that the ancient moraine of the ordinary type was deposited between the two bear-den moraines instead of outside the two, as in the case of the latter.

c. Rate of retreat. The only possible data for any estimates upon the rate of retreat up the valley must be drawn from a study of the forest trees and no one realizes any more strongly than the writer how unreliable and misleading such data may be. However, we may obtain an approximate minimum estimate by this means, which may have some interest, if not real value. Some exceptionally large spruces and hemlocks are found near the mouth of the valley and within the outer bear-den moraine. Based upon the average thickness of the rings of growth, noted upon page 96, two of the largest seen should be 525 and 598 years of age, respectively. Toward the schist cut, at the head of the valley, the rings of growth become coarser and the trees smaller, the difference in elevation amounting to about 900 feet. One of the largest firs showed 161 rings of growth and a still larger hemlock growing near was estimated to have lived about 250 years. Assuming that it required about the same length of time for the trees to get started at either end of the valley, it took the Asulkan about 350 years to retreat the two miles from the mouth of the valley to the schist cut, or at the average rate of about 30 feet a year. From the schist cut to the present nose, about one-quarter mile, the valley opens and the retreat must have been much slower, owing to the volume of ice to be melted away. If we assume that it required 50 years for the hemlock noted to get started, the minimum time involved would be 300 years and the maximum average rate of retreat for this part of the glacier would have been about 4.4 feet per annum. If the cut in the schist

FIG. 1.—Development of ice seracs from glacial blocks, Asulkan Glacier, August, 1904.

FIG. 2.—Disrupted quartzite blocks, near head of Paradise Valley, Canadian Rockies. Illustrating plucking power of glaciers.

has been made entirely since the withdrawal of the ice from that part of the valley, then the rate of cutting would be over an inch a year, which is probably too fast for even water at high velocity, charged with glacial sediment and operating upon rather soft rock. This seems especially true when we consider that the supply of water is much reduced, or possibly entirely shut off during the greater part of the year. It is very probable, however, that the narrow gorge may have been largely formed subglacially, while the glacier extended far down the valley. Schist layers upon edge do not well record ice action, but even if such evidence of glaciation was present it may have been destroyed by subsequent weathering. It must be noted that the time of retreat determined as above would represent only a minimum value and the rate of movement per annum for a definite distance would represent a maximum.

CHAPTER VIII.

SUMMARY AND CONCLUSIONS.

In the closing chapter it is desired to give a concise statement of the most important results secured in the two seasons' work and the conclusions reached. The writer desires further to express for the benefit of those who may be interested his conviction concerning some of the theoretic questions that have arisen in connection with the study of these Canadian glaciers.

1. Physiographic Changes in the Region.

a. Mesozoic peneplain. From the close of the Archæan to the end of the Laramie, conditions were very favorable for the accumulation of sedimentary deposits in the region now covered by the Canadian Rockies and Selkirks. Strata belonging to the Palæozoic and Mesozoic eras of the world's history reached the extraordinary thickness, according to the work of Dawson and McConnell, of 50,000 to 60,000 feet. Much of this was brought above sea-level during the Mesozoic era and further sedimentation ceased except in certain restricted regions in the eastern part of the area, where conditions were still favorable for marine or fresh-water accumulations. During countless ages of exposure to the manifold atmospheric agencies there was developed a broad Mesozoic peneplain, extending in a direction to the west of north and sloping eastward and westward, determining the general direction of flow of the drainage streams. It was during this stage, probably, that the mountains suffered their greatest denudation, rather than since. The great Laramide revolution of the western United States and Canada completed the formation of these mountains, the pressure coming from the west in the region under consideration, and producing a series of parallel folds and troughs, with numerous overthrust faults, all having a north-northwest to south-southeast trend. The upheaval was slow enough so that many of the original drainage streams were able to maintain their general direction of flow, cutting their way continuously across the gradually rising ridges of the mountains and the lesser folds of the foot-hills. In many cases, the troughs, lying between parallel ridges, or the gaping crevasses in the rock strata parallel with them, captured the drainage and a system of longitudinal river courses was developed, much younger than the transverse system. As a result of these great orogenic movements, combined with the atmospheric and aqueous agencies operating since, we have an uplifted and dissected peneplain.

b. Pre-pleistocene erosion. With the completion of the mountains at the close of the Mesozoic, the more or less sluggish streams of the ancient peneplain acquired velocity and renewed their activity, cutting deeply into their former beds. The newly born longitudinal streams incised still further the channels provided for them and there were developed two systems of V-shaped valleys more or less intimately connected. The agencies of weathering broadened the valleys above and delivered the rock fragments to the stream below, by which tools the water still further deepened its beds. This action went along slowly from the beginning of Cenozoic time to the beginning of the Pleistocene, during which time the roughly angular blocks were carved into jagged peaks and many of the divides into sharp-crested ridges. The outline of the old peneplain is to be recognized only when one ascends until his eye is on a level with its uplifted surface, when peaks and ridges all blend into the common level that cuts the sky at the limit of vision. See plates II, XVI, and XXXII.

c. Pleistocene erosion. The opening of the Pleistocene and the advent of the glaciers introduced a new geological agent into the region. A reduction in the mean annual temperature, combined with an increase in precipitation, allowed the snow to accumulate about the higher peaks and ridges more rapidly than it could melt away during the warmer season. Year after year the snow banks thickened, sent their avalanches into the valleys faster than they could melt away, and thus the mountains became enveloped in snow and ice. Glaciers moved down from the more elevated valleys, joined forces with their neighbors, grew in volume and power, took possession of the river valleys, and sent massive tongues of ice far beyond the limits of the mountains. The valleys were filled to depths of 4,000 feet from their floors, in certain cases, the actual elevation rarely falling below 7,000 feet above sea-level. These ice streams exercised a powerful effect upon the rock strata over which they passed; in general, rounding and smoothing their outlines, cutting down prominences, and truncating mountain spurs. In some cases where plucking was most active the rocks were made still more jagged and irregular than the ice had found them. The lower half of the valleys, which had been invaded by the ice, had their floors broadened and their sides correspondingly steepened, giving this portion of the valley a U-shaped cross-section. The upper portion, under less pressure of ice, still retains more or less of its pre-pleistocene V-shaped form, the sides being simply smoothed and fluted. The extension of these V-slopes until they intersect in the valley may be assumed to mark the level, approximately, from which the glaciers began deepening their beds. In the floors of the valleys at certain places rock-basins were gouged out, either because of the structure or softness of the rock or because of the more vigorous ice action for a limited distance. At the heads of the separate valleys, broad semicircular amphitheaters, or cirques, were cut out, an interesting series of which is shown in plate XXXIX, figure 2, at the right side of the view.

From observations made upon the plucking power of glaciers in the various valleys, the writer is quite prepared to admit the sufficiency of glaciers as engines of erosion, especially where the ice is very thick, concentrated in its action, and operates for long time over stratified, or much jointed formations. In addition to the plucked mountain peaks observed in the Yoho Valley (page 79), there is to be seen in Paradise Valley, lying between Lake Louise and Moraine Lake, a very striking case of plucking, in which very heavily bedded quartzite has been bodily removed. The upper stratum is 10 to 12 feet thick, and about the margin of the stratum, the upper surface of which is very perfectly glaciated, immense blocks, some of them as large as small houses, have been started a short distance and then left. Apparently in the waning stages of the glacier the ice had been unable to get hold of blocks which it had been able to pry loose from the parent bed. This occurs near the head of the valley and it is difficult to resist the conclusion that hundreds of feet of similar, or less resistant rock may have been removed between this ledge and the mouth of the valley. Glaciers with their basal layers shod with hard rock débris would be able to erode slowly. The amount of erosion accomplished in this way would depend simply upon the time, but it has probably always been small, when compared with that due to plucking. It seems likely that pure ice can have only an insignificant effect upon ordinary rock, when simply pushed across it. The greater the pressure the more the melting, and unless disruption of the rocks occurs, the only effect would be to give the rock a polish.

d. *Pleistocene deposition.* During the maximum stages of glaciation there were so few overtowering cliffs above the névé fields and the ice streams themselves that very little supra- and englacial material was carried. In consequence during the stages of halt, that must have succeeded one another in the retreat from the outermost position attained by the trunk streams, no great, conspicuous moraines were formed. Not until the glaciers had retreated to near the heads of the valleys do we find prominent terminal moraines. At this stage the level of the ice and snow has dropped below the cliffs so that it is possible for the glaciers to acquire, in many cases, a heavy load of rock débris upon their upper surfaces. Glaciers like the Yoho have still been unable to build prominent moraines from materials carried supraglacially. The detritus resulting from the destruction of rock strata in the valleys and over the rocky slopes was carried near the bases of the glaciers, or pushed and rolled along between the ice and its bed. This resulted in the making of much ground moraine, much of which remained in the valleys in places favorable for its lodgment. During the maximum stages of glacial development much of this subglacial material was carried beyond the mountains and deposited as till, or it found its way into the rapid streams, where it was immediately assorted into boulders, cobbles, gravel, sand, and clay. In these various forms it was built into the terraces, flood plains, deltas, etc., which characterize the drainage streams. The finer materials made their way to the Pacific and Hudson Bay. The argument against great glacial erosion that the material removed cannot be found, seems to the writer to carry little weight. If one looks far enough and is able to distinguish the Pleistocene and post-pleistocene deposits from the earlier, it seems probable that enough would be located to restore the mountains and valleys to the condition in which the glaciers found them. In the Bow and Cascade valleys, near Banff, Wilcox discovered two distinct till sheets, indicating that there were, at least, two main advances of ice through this section of the mountains. Eastward from the mountains McConnell and Dawson found three such sheets, derived either in whole or in part from the Rockies.

2. Precipitation.

a. Geographic distribution. Owing to the north to south trend of the four mountain systems that here constitute the great Cordillera, their limited breadth, their nearness to the warm waters of the Pacific, and the relation of the region to the great cyclonic areas that enter from the Pacific, conditions are favorable for an abundant precipitation upon the western slopes of the mountain systems. The arrangement of the four systems being such that they increase in height successively from the Coast Range to the Rockies, enables all of them to get a fair share of the available precipitation. The prevailing winds are from the west and laden with moisture. In ascending the windward slopes much of this moisture is precipitated as rain, or snow, owing to the expansion and consequent cooling of the air. In the condensation of this moisture its latent heat is liberated and raises the temperature of the air. In being drawn down the leeward slope by the general cyclonic movement of the atmosphere, the air is still further warmed by the compression to which it is subjected, its capacity for holding moisture is increased, and it reaches the same elevation upon the leeward slope much dryer and warmer than it was at the corresponding level upon the windward slope. This gives rise to the well-known "chinook wind," the equivalent of the Alpine foehn. The Selkirks, lying to the west of the Rockies, receive the heaviest precipitation, are more completely forested, experience more frequent avalanches of snow, and send their névés and glaciers to lower levels. The shifting of the centers of the cyclonic areas to the south of this region would give rise to prevailing easterly winds, which in the winter would be colder and dryer and in the summer warmer than those which now prevail, and, without doubt, bring about the disappearance of glaciers from this part of the mountains.

b. Climatic cycles. Precipitation records are too scanty and fragmentary for safe generalization concerning the occurrence in this region of oscillations known to occur in the other parts of the world. Still there are several lines of evidence which indicate that a phase of reduced precipitation closed in the Selkirks and Rockies about the year 1897 or 1898, and that since then the average for the series of years is in excess of the normal. These lines of evidence consist (1) in the records kept by the station agent at Glacier House of the snowfall, and of the records of the Canadian Meteorological Service for Banff and Calgary. With the exception of Agassiz, which appears to be one of Brückner's "exceptional coast stations," the other records do not reach far enough back to be of service. (2) The notes and photographs of the Messrs. Vaux in the Asulkan Valley, made in 1898 and 1899, when contrasted with those of later date, indicate the close of a series of years with 1897-8, during which the snowfall was much less than since. (3) The thickness of the strata in the névé of the Asulkan Glacier, assuming that they represent annual accumulations, indicates at the point photographed in 1902 that three years of diminished precipitation closed with 1897-8 and were followed by four years during which the average precipitation was in excess. (4) In 1883 and 1884 Dawson found over a belt of country 140 miles long in the western part of the Rocky System, evidence of a recent high-water stage of the lakes, which resulted in the killing of trees that must have grown during a prolonged low-water stage that preceded. The condition of the trees indicated that they had "been killed within a few years." If we assume that the wet phase that gave rise to this condition of the lakes closed about the year 1880, then we should expect the inauguration of another wet phase about the years 1897 or 1898. Finally (5), from the photographs that have been made of the Illecillewaet Glacier we have proof of the long-time oscillations of the level of the ice about the névé line, giving rise to

c. Ice waves. When photographs taken from the identical view-point in 1888, 1897, and 1905 (plates XXXVI and XXXVII) are compared, they show a marked fluctuation in the height of the ice along the sky-line. The ice appears to have been at a minimum about 1888 and to have been approaching the same condition in 1905, possibly attaining it during the current season of 1906. The crest of a wave, or impulse of ice from the névé appears to have reached the sky-line about 1897 to 1899. The time from trough to crest would represent a quarter of the period, that from trough to trough, half of the period of the complete oscillation of the ice wave. In this case our data would indicate a period of 36 to 40 years, agreeing well with the precipitation cycles to which these ice waves are to be ascribed. It has been shown by the work of Finsterwalder, Blümcke, and Hess that the advance of a glacier is due to the progress of an ice wave along its length, moving more rapidly than the ice itself. The Illecillewaet in 1887 was experiencing about its nose the last stages in the effect of the arrival of such a wave. The trough, then at the sky-line, moved valleyward and permitted the retreat of the nose of the glacier, which retreat was probably at its maximum about the year 1895 or 6, or some 8 or 9 years after the start. The data for 1902 to 1905 seemed to indicate that an advance was about to be inaugurated but the very marked retreat of 1905-6 shows that this advance has been somewhat delayed. When later the year is known at which date the advance was most rapid we may figure the rate at which the wave travelled the length of the glacier. It is a matter of much interest to try to connect the crests and troughs of these ice waves with the corresponding wet and dry phases of the precipitation cycles noted above. Since the crest of the wave arrived at the sky-line in 1897–9, just at the close of the dry phase and the beginning of a damp one, the wave must be referred back to the damp phase of the preceding climatic cycle, closing in the late 70's, or early 80's, so far as we may judge from the observations of Dawson upon the level of the lakes in the western Rockies. This would give the "reservoir lag" of one-quarter of the period, required by Reid's calculations, and an additional 16 or 18 years for the impulse to reach the crest of the rim. The trough resulting from the dry phase closing in 1897 appears to have moved out from the reservoir more promptly, possibly owing to certain local conditions.

3. Piedmont Type of Glaciers.

Three representatives of this unusual type of glacier were found, two of which, the Wenkchemna and Asulkan, are here described; the third is the Horseshoe Glacier at the head of Paradise Valley, in the Rockies. This type of glacier is always compound, being made up of a series of glaciers of the common Alpine type, all of coördinate importance, which coalesce laterally but retain their individuality from névé to nose. Since none of them are *tributary* to any of the others, but independent in all essential respects, they are here referred to as *commensal* streams, in order to indicate this relationship. These separate streams have temporarily united forces and found strength in the union. In the case of the Wenkchemna it is very probable that very few, if any, of the commensals could exist separately. In its earliest stage of development the piedmont glacier begins as a series of Alpine glaciers, either with or without tributaries, lying in neighboring valleys. With the increase in precipitation the level of the surface of the separate streams rises until they cover the divides between adjacent streams, or the, at first, separate Alpine glaciers reach out upon the *pied-mont* and there coalesce laterally. In its senile condition, a stage to be reached sooner or later, the piedmont glacier returns to its condition of youth and disintegrates into its component streams, as illustrated by the Asulkan of to-day. In the case of the Horseshoe Glacier some sixteen different commensal streams may be recognized, the most western four or five of which have almost completely separated from the others. The glacier has a meager snow-field, the supply for which is avalanched from the slopes of Mts. Ringrose (No. 10), Hungabee, Lefroy, and the southern side of the Mitre. Observations upon the Wenkchemna showed that each separate nose may have its own independent behavior and that the movements of the glacier as a whole cannot be known unless data are collected for each component stream.

4. Parasitic Glacier.

From the hanging glacier upon the eastern shoulder of Mt. Lefroy there is avalanched to the back of the Mitre Glacier quantities of snow and ice, falling a vertical distance of some 2,000 feet and accumulating along the base of the cliff. The ice of the glacier is broken into fragments, some of it disintegrating into its component granules and much of it ground into ice dust, destroying completely the stratification and lamination of the hanging glacier. The avalanches occur mainly during the late spring, summer, and early fall, and as a result of the spreading of the fragments from sliding and rolling there is made each season a stratum of ice similar to those ordinarily found in the névé region. Regelation is complete and there arises what is known as a reconstructed, or regenerated glacier, with its strata leading to and dipping towards the region of accumulation. The weight of the ice here forces the lower strata to move out at right angles to the cliff face and a forward movement is imparted to the ice directly across the Mitre Glacier upon which it rests. This regenerated Lefroy moves about one-half as fast as the underlying Mitre, so that before the latter has reached the Victoria, the Lefroy has crossed to the opposite side of the valley. Between the hanging Lefroy Glacier and its bed there is being manufactured a certain amount of ground-morainic material, which is incorporated into the strata of the regenerated Lefroy, and moved across the valley as a result of its motion. While this is taking place, however, the Mitre is carrying the entire Lefroy down the valley and the actual motion of the débris is the resultant of these two motions by which there is accumulated at the base of Mt. Aberdeen a great heap of ground-morainic matter, with a dressing of angular material from the face of the latter mountain. The ground moraine rests upon the back of the Mitre and some of it is ridged parallel with its side, in which form it is dealt out to the Victoria and constitutes the main bulk of its right lateral moraine. This Lefroy Glacier is distinct from the Mitre, upon which it rests, in that it is a different type, is nourished differently, has a different form, a distinct set of strata unconformable with those of the Mitre, has a different direction of motion, a different rate of motion, and is accomplishing a wholly different geological work. The glacier is *parasitic* in the sense that it is carried by its host and is nourished from snow and ice that might otherwise be available for it. It is not parasitic in the sense that it draws its sustenance from the Mitre itself.

It is probable that glaciers of this type are now, and have been, more common than has been generally recognized. It seems likely that at a certain stage the glacier in a hanging valley would sustain more or less of this relation to the trunk glacier. By means of such a glacier we may account for the lateral transportation of materials across a valley and a transportation that would leave no record upon the bedrock. If two distinct glaciers may occupy the same valley simultaneously, it seems probable that two ice sheets of the continental type might be superposed, flowing in different directions, the upper delivering material to the lower.

5. Bear-den Moraines.

The bear-den type of moraine is so exceptional that some special explanation must be found by which we may account for the accumulation of coarse mountain fragments without the usual filling of fine materials. The size of the blocks themselves is not so remarkable, knowing what a transporting agent a glacier is, as the *average* size of the fragments making up the moraines. In the case of four of the five glaciers studied, two of these moraines were found and only two. The absence of them in the case of the Yoho is readily understood when the lack of high cliffs is noted. Not one of the glaciers at the present time could form such a moraine, no matter how prolonged the halt. The blocks are angular and show no more glaciation than they might have received upon one face while they were in their original position in the cliff. The blocks were carried upon the ice and were not pushed or dragged along in front of, or beneath it. The fine material was not removed by the action of running water, as might have been done in other cases; but was absent from the first. If we are to account for these moraines we must load the glaciers with a mass ot exceptionally coarse blocks and only a minimum of fine débris. This cannot be done by assuming two periods of excessive weathering for they would produce as much fine material as coarse, and very probably a great deal more. The prevalence of the phenomenon prevents our resorting to the ordinary rock slide for our explanation. In the case of the Victoria it built a moraine of the ordinary type, then the two bear-den moraines, and then the present modern moraine essentially like the first. The Asulkan built its outer coarse moraine, then one of the ordinary type, then its younger coarse moraine and subsequently a series of the common variety. An examination of the various cliffs, in connection with each of the four glaciers, from which the material was most certainly derived shows that they all have a trend from north-northwest to west-northwest. A further suggestive fact is that in all cases the bulk of the material fell to the eastward.

During the season of 1904 no plausible explanation occurred to the writer, but upon leaving the field the idea of a double seismic disturbance came up and was carried back to the mountains in 1905. It seems now to be the only explanation by which to account for the phenomenon. Slipping may have occurred along some of the numerous fault planes traversing the eastern Rockies in a north-northwest direction and the region crossed by westerly moving seismic waves. From cliffs having a general northwest-southeast trend, blocks, already much weathered, would be detached and thrown eastward, comparatively few falling from the westerly facing cliffs. Glaciers most favorably situated for acquiring a load by this means, as the Wenkchemna, have the most massive deposits of the nature described; those unfavorably related to high cliffs, as the Yoho, appear to have made none. The great blocks detached by the earth jars fell into soft névé, or upon the yielding ice, and were not ground into small fragments as they usually are when they descend to the valley floors. The protection afforded the ice by the material brought about a halt of the front, until the blocks were deposited, when the general retreat was resumed.

It was reasoned that if the disturbances assumed reached from the Great Divide to the Selkirks, then many other glaciers, equally favorably situated for acquiring a load by this means, should show the same type of moraine, if they were not tributary to other ice streams at the time. Further we should expect to find occasional rock slides of the same age as the moraines and cliff débris that did not reach the back of a glacier. The latter material not being concentrated would be inconspicuous. In 1905 there was but little time for a general examintion of the region but visits were made to the Horseshoe and Geikie glaciers. The former lies between the Wenkchemna and Victoria, with its main extent of vertical cliff extending to the northeast, but with a considerable portion extending from Hungabee to the Wastach Pass, with a westerly to northwesterly trend. Opposite this portion of the glacier there is a deposit of very coarse blocks, that were dropped upon the crest and outer slope of a still more ancient moraine, consisting largely of a stony till. The number, however, is very meager compared with those in the Valley of Ten Peaks, and would call for no exceptional explanation. A low ridge of coarse blocks occurs just inside, showing best about the front of the nearly detached western portion of the glacier, which is correlated with the inner of the bear-den moraines. In the case of the Geikie Glacier, lying at the head of Fish Creek Valley and nourished from the southern portion of the Illecillewaet névé (plate XXXIII), no moraines of the type sought were found within a distance of one and one-half miles of the nose. Although the cliffs are sufficiently steep to have supplied the material their general trend is northeast-southwest, *i. e.*, in the direction of supposed earth movement, and they suffered relatively little destruction. From the eastern face of Mt. Burgess there has been dropped a mass of coarse rock, which more strongly suggests the morainic deposit seen in the valleys than that seen anywhere else outside the reach of the glaciers. In many of the talus slopes there are many coarse and fine blocks, which look to be of nearly the same age, instead of showing the gradation that we might expect. In their work referred to upon page 4, Collie and Stutfield describe a mass of rock débris in the valley of the Athabasca (page 126) that may represent one of these ancient coarse moraines or a modern one in process of forming. In referring to peaks Woolley and Stutfield they say, "These two last mountains appeared to have been conducting themselves in a most erratic manner in bygone ages. A tremendous rock-fall had evidently taken place from their ugly bare limestone cliffs; and the whole valley, nearly half a mile wide, was covered to a depth of some hundreds of feet with boulders and débris. What had happened, apparently, was this. The immense amount of rock that had fallen on the glacier below Peak Stutfield had prevented the ice from melting. Consequently the glacier, filling up the valley to a depth of at least two hundred feet, had moved bodily down; and its snout, a couple of hundred feet high, covered with blocks of stone the size of small houses, was playing havoc with the pine-woods before it and on either side. In our united experiences, extending over the Alps, the Caucasus, the Himalaya, and other mountain ranges, we had never seen indications of a landslide on so colossal a scale." In a footnote they add, "The remains of a similar landslide were afterwards noticed blocking the outlet to Moraine Lake in Desolation Valley."

If the seismic theory furnishes the true explanation of these double massive moraines, then we have a means of correlating the positions of the extremities of all the glaciers showing them at these two stages in their history, also data for determining their actual retreat since and their relative rates. Glaciers, that were not tributary to others at the time, confined between steep cliffs, having a northwest to southeast trend, may be expected to show such moraines. There is the possibility that any particular glacier may have advanced since and have overridden one, or both, as the Victoria and Wenkchemna have partially done with the inner of their series. Numerous earthquakes must have occurred during the long Pleistocene period, but the cliffs were so completely blanketed in snow that we find no such records left in the trunk valleys. Similar moraines should be found in other sections of the world, but they might originate from the removal of the finer materials by running water, as well as by earthquakes and simultaneous rock slides. As to the actual age of these moraines we may only loosely speculate. The blocks *look* old and the schists and sandstones have disintegrated more or less, *in situ*, but undoubtedly they were badly weathered before the glaciers got possession of them. The age of the moraines is to be expressed in centuries rather than thousands of years. Based upon our vegetation data we may conclude that the inner of the two moraines was completed about five or six centuries ago and that the earthquake disturbance responsible for it may have occurred two centuries earlier. The outer of the two moraines seems to be about two centuries older.

6. Surface Features.

a. Dirt bands, zones, and stripes. In Chapter III of this report the writer has described and figured these three glacial features and has suggested that certain terms, used rather indiscriminately for any one, be restricted to a single feature. The first two are very often confused, one with the other, but are so essentially different in their real nature, if not always in their appearance, that they should be sharply separated and differently named. The *dirt zones*, or simply the *zones*, when the foreign matter is not present to discolor them, are the outcropping edges of the strata of which the glacier is composed. They show to best advantage about the nose and lower margins of the glacier that is sufficiently free from débris, as broad, parallel zones encircling the lower extremity and passing around to the sides where they disappear. They are usually convex down-stream, but the form they assume is determined by the configuration of the glacier's extremity. In case the stratification in the glacier is absent for any cause, there can be no zones seen.

The *dirt bands* are entirely superficial and result from the collection of fine débris in long hollows or troughs that first extend transversely across the glacier, but which become convex down-stream from the more rapid central motion of the ice. They occur in series, roughly parallel and regularly spaced, and assume finally a pointed, or hyperbolic form, which probably suggested to Schlagintweit the term "ogiven." The name "dirt band," however, was originally assigned to them by Forbes, their discoverer, and is in more general use. The transverse, parallel troughs, in which the dirt bands have their origin, arise from the incomplete healing of transverse crevasses which occur at the crest of a steep ice slope. The lips of a crevasse, exposed to intense solar action are rounded more or less and when the crevasse closes there is left a trough which marks the position of the original crevasse. Into this depression wind-blown dust collects and is washed from the adjacent slopes. By absorbing heat this dust may emphasize the depression slightly and may render the ice somewhat spongy, as pointed out by Tyndall. If the ice slope is too steep, a cascade results and the ice is too much shattered to show the bands, or to allow them to form. If the slope is steep, but regular, with much melting over the surface, the site of the bands will be destroyed before any complete series can develop. Conditions are most favorable for their production upon the face of a moderately steep slope, which is immediately followed by a long stretch of gently inclined ice. They sustain no necessary relation, whatever, to the dirt zones, being present when the zones are absent. When both zones and bands are present they may be comformable for a greater or less distance and may be difficult to distinguish from one another. In the case of such a glacier as the parasitic Lefroy the zones and dirt bands may be discordant and intersect at high angles. There is reason for thinking that the dirt bands are produced annually, only the summer formed crevasses furnishing the necessary troughs, while the few winter crevasses completely and perfectly heal in passing down the slope. If this proves to be the case we have a means of determining the approximate yearly motion of the ice along the slope and a clue to the extent of the longitudinal compression, or extension, of the ice subsequently.

Where the edges of the blue bands, embedded in the more porous whiter ice, outcrop upon the surface, particularly along the margins of the glacier pressing firmly against the valley wall, there is developed a further miniature banding. The firmer blue ice melts less rapidly than the more vesicular layers and a series of parallel ridges and troughs results, the course, distance, and average breadth of which is determined by the ice structure itself. In the narrow troughs the fine dirt collects and the ice is marked with a series of delicate parallel dirt streaks. Tyndall compared them with the marks left in a gravel walk by a garden rake. Drygalski describes them under the name of *Schmutzbänder*, but this term must be reserved for the true dirt bands of Forbes. *Dirt stripes* suggests their appearance and will enable them to be distinguished from all the other dirt features. In that they owe their existence to the actual structure of the ice they have some relationship with the dirt zones, but in that the dirt of which they are composed is purely superficial, they are more nearly related to the dirt bands. They are to be seen at only a short distance, while the zones and bands are best brought out from a distant, elevated view.

b. Differential melting effects. Under favorable circumstances an interesting series of stages may be passed through by dust wells; dirt, sand, and gravel cones; boulder mounds; lakelets and morainic ridges. This was first worked out by Russell upon the Malaspina for the lakelets and boulder mounds, but it applies also to the other features as well. Dust wells may persist through a season, or a series of seasons presumably, the dirt patches to which they owe their existence being continuously retained in the miniature wells. Although very shallow at any one time, their total depth might measure many feet. From wind action and small trickles of water more dust is being added slowly and in time there may be enough to protect the bottom, instead of causing its melting. The dirt now appears at the surface and the ice beneath melts less rapidly than the unprotected adjacent ice, giving rise to a miniature cone, marking the original site of the well. Such cones are found of various sizes and covered with dirt, sand, or gravel. By lateral melting the slopes eventually become so steep that the veneering slides off, or it may be washed down by heavy rains and distributed about the base of the ice cone. The bare ice is now attacked by the sun and a hollow is produced where the cone stood, about the rim of which stands more or less of the material by which it was covered. This material rolls and slides back into the depression as the sides are widened and steepened by melting. When enough has been concentrated at the bottom and about the sides to prevent further melting, the adjacent ice which has lost its protective cover, just in proportion as the depression has gained, now melts away to a level with the bottom and then still lower, causing the material collected in the basin to again assume the form of the cone. The miniature examples of this action might pass through these stages several times in the course of the season, while the boulder mounds and lakelets would require many seasons for the completion of a single cycle. In the case of a medial moraine, or a lateral resting upon ice of sufficient thickness, the same stages may be passed through, except that when the material is shed it assumes the form of a double ridge, between which the elongated trough is developed and into which the débris may slide to produce a single ridge again. In this way the superficial débris of a glacier may be subjected to much tossing and bruising before it comes to rest in the frontal or ground moraine. In the case of a débris-covered ice surface all that is necessary to start the process is to have the material unevenly distributed, a little thinner or a little thicker patch of foreign matter.

7. Ice Structure

a. Stratification. From a comparison of the thickness of the strata in the Asulkan with the available records of snowfall it seems probable that the strata in this glacier, as well as in the Illecillewaet and Yoho glaciers, represent the annual accumulation of snow in the region. The fall snows are combined with those of the following winter and spring, compacted by the summer's melting and rainfall into a white, porous stratum of granular ice. At any given place upon the névé by means of wind action a stratum may have gained, or lost in thickness. Owing to the deposition of the snow in successive layers and the periodic distribution of wind-blown rock débris, each stratum acquires a more or less distinct lamination; conformable with the stratum itself. During the summer melting the fine dirt is concentrated at the surface, forming a soiled streak which contrasts strongly with the fresh snowfall of the fall. The water resulting from the surface melting and rainfall sinks into the stratum and contributes to the growth of the névé granules, forming a crust of different texture and color, by which the strata may be distinguished when no dust is present. In the case of a regenerated glacier, such as the Lefroy, the stratification results from periodic avalanching of snow and ice during the late spring, summer, and early fall. The strata may vary much in thickness and have no immediate connection with the amount of precipitation. They may become charged throughout with ground-morainic material and give rise to very distinct zoning. When a glacier is fed in part by névé snow, and in part by avalanches from hanging glaciers the stratification may appear very irregular, as in the case of the Victoria. In passing an ice cascade the stratification and lamination may be completely destroyed, or the uppermost strata may be destroyed and the lower more or less perfectly preserved, as pointed out by Reid. It is not supposable that the stratification could be thus destroyed and the more delicate lamination preserved. In the case of the regenerated Lefroy the stratification is restored, after having been lost, but it is not possible to restore the lamination completely, or regularly, in the case of such a glacier. It should be noted in this connection that under exceptional conditions shearing planes may be developed in the body of the glacier which do not coincide with the limiting planes of the depositional strata. In this way there may be acquired another type of secondary stratification having no relation whatever to that which originates in the névé.

b. Shearing. Observations upon the oblique front of the Victoria in 1904 indicated that the upper strata were moving bodily over those upon which they rested. The upper strata projected more and more daily, when there was not enough additional débris in the lower to account for the phenomenon by differential melting. A small amount of sand and fine gravel, washed down from above, collected in the lee of the upper projecting layers. Some days this was in small enough quantity to accelerate the melting of a narrow strip of ice upon which it rested, but quite as often melting was retarded by the material. At one place where the shearing action seemed pronounced three heavy spikes were driven into the base of the upper stratum and three corresponding ones in the face of the subjacent layer. These spikes were six inches in length and were driven horizontally into the ice until their heads were flush with the surface, about eighteen inches apart. The average surface slope of the ice was 46° and the vertical height of the ice 50 to 52 feet. The upper stratum had a thickness of about three feet, the lower two feet, and each contained, apparently, about the same amount of foreign matter, and this small in amount. At the beginning of the observations the upper stratum projected 19.7 inches beyond the lower (July 21), and by August 3, 25.6 inches, showing a gain in the 13 days of about six inches of the upper beyond the lower. The spikes were visited daily and reset and showed that while the upper stratum was advancing with reference to the lower it was also melting back more rapidly, because of its more exposed position. The average daily melting about the spikes in the upper stratum was 0.23 of an inch in excess of that about those in the lower and proved that a differential movement of the strata was taking place.

c. Blue bands. It seems highly desirable to distinguish the minor stratification seams, originating in the névé, from the blue bands, blue veins, or ribbon structures, that have had an entirely different origin. The first step toward such distinction is to have a separate term for each of the two types of structure and the writer suggests that *laminæ* be used exclusively for the minor layers of which the strata are composed and that *blue bands*,[1] already in such general use, be restricted to the structures commonly included under the term, however they may have been produced. When they are each made the object of comparative study it should be possible to distinguish them. We should naturally expect the laminæ to become less and less distinct toward the nose, and to appear continuous, while we find the blue bands there showing very typically and being discontinuous. The same stratum might show both structures, either conformable, or cutting one another at various angles. In the case of simple glaciers, Agassiz and Reid have succeeded in tracing the laminæ from the névé to the nose. The structures seen in the Canadian glaciers are blue bands, rather than laminæ, since they are developed in great perfection where the strata have been completely destroyed, as in the case of the regenerated Lefroy and almost obliterated as in the Yoho and Illecillewaet glaciers. In general their position is at right angles to what may be assumed to be, or to have been, the direction of maximum pressure. They are seen best along the margins where the glacier is closely confined between rocky walls, extending parallel with the sides, dipping downward and inward at a steep angle. Beneath the medial moraine upon the Victoria they are vertical to fan-shaped. At the foot of ice cascades they may extend crosswise of the glacier. Having the same origin and being essentially alike, it does not seem wise to use different terms by which to separate these, such as marginal structure, longitudinal structure, and transverse structure, as suggested by Tyndall. Contorted patterns and faultings are to be accounted for by assuming differential movements in the ice after the formation of the bands.

When followed for a short distance, in either direction, blue bands are found to thin out to an edge and disappear, showing that they have a very flat, lenticular shape. Separate bands overlap and are felted together as are the bands in a schistose or gneissic rock. They strongly suggest schistosity in rocks and not stratification. The ice of which each band is composed is more compact, more free from air bubbles, and a deeper blue than the ice in which it is embedded. That they have been produced by pressure and stand at right angles to it, when in process of formation, as demonstrated by Tyndall, seems most probable. That

[1] The term *band* alone, or *banding*, as suggested by the glacial conference in August, 1899, is not fully satisfactory since it does not distinguish this structure from the dirt bands of Forbes. The following terms have been applied to this structure by various writers; Bandstruktur, Bänderung, Blaubänderung, Blätterstruktur, Blaublätterung, Blaublätterstruktur, blaue Bänder, blaue Streifen, Schieferung, Schichtung, parallele Struktur, stucture rubanée, structure lamellaire, ribboned structure, blue veins, blue leaves, blue bands, lamellæ, laminæ, lamination, and stratification.

these bands represent portions of the glacier that have been completely liquified by pressure, allowing the air bubbles to escape, seems, to the writer, very improbable, for four reasons. (1.) Blue bands occur in the basal layers, parallel with the valley floor. The thickness of the ice of an ordinary glacier is not sufficient to induce general melting by its simple weight. (2.) If the granular structure of the glacier is completely destroyed by melting, it cannot be reproduced by simple freezing, and still the granules are best developed in the blue band areas. (3.) Occasional granules may be found which extend from the blue bands into the adjacent vesicular ice. (4.) Water freezing in cavities in the body of a glacier should form a series of prisms, standing with their main axes at right angles to the ice surfaces bounding the cavity. Such filled cavities are found in the ice but they do not constitute blue bands.

d. Ice dykes. In connection with the Lefroy Glacier chiefly, there were noted in the early summer what appeared to be former crevasses, filled with ice and forming ice dykes in the body of the glacier. Some of these were cut by crevasses, testifying to their greater relative age and suggesting that they might persist from one season to another. A few of the dykes contained granular ice, the granules being moderately coarse, and were assumed to have been formed by the filling in of crevasses with ice avalanched from the hanging glacier upon Mt. Lefroy. Most of the dykes, however, were completely filled with a double tier of ice prisms, having their bases attached to the walls of the crevasse and extending horizontally out into the cavity, at approximately right angles. Generally the prisms met at the centre those from the opposite face of the crevasse and their inner ends interlocked. Sometimes a space was left between the opposite tiers of prisms. Ellipsoidal shaped spaces were also found completely filled with radially arranged prisms meeting at the centre. The explanation given for these features is that they were formed by the freezing of water in crevasses, and other cavities, in the spring, or early summer, while the glacier still retained a sufficient degree of its winter's temperature. The water was supplied by the early melting, or rains, and the freezing surfaces were the walls of the crevasse, instead of the lower stratum of the atmosphere, as is usually the case. Since in freezing, water forms a series of parallel prisms, with their axes lying, as a rule, at right angles to the surface of refrigeration, these prisms have the abnormal horizontal position, instead of the usual vertical one. Although the upper part of the dyke may have been lost by melting, there was no evidence that a horizontal stratum of ice had formed across the top from freezing induced directly by the atmosphere.

Drygalski has argued that it is *pressure* that determines the direction that the crystalline plates will assume when water is freezing, and that the main prismatic axes will lie parallel with this pressure. In the case of the ice of a lakelet or basin, after it has once been enclosed by the ice cover, the under side will be subjected to an upward pressure owing to the gradual expansion of the water as it is brought to the temperature of freezing. But the orientation of the basal plates, parallel with the upper surface, began before the cover was completely formed and hence before such pressure could have come into operation. As pointed out by Mügge they also assume this position when an opening through the ice cover is artificially maintained. Mügge believes that the plates are simply floating in their position of equilibrium and that the pressure has nothing to do with the orientation of the plates. That this, however, is not the cause of the orientation is shown by the position of the columns in the ice dykes above described, where the plates have formed in a *vertical* position, while in the case of the ellipsoidal water-filled cavities they have formed at all angles between the vertical and the horizontal. In the case of the ice dykes the formation of an ice cover would have given rise to a lateral pressure, as well as an upward one, and the position of the plates in the horizontal columns would have been in harmony with the view of Drygalski. No trace of this cover, however, was seen, and it seems probable that the columns would still have formed at right angles to the cold walls of the crevasse, under none other than hydrostatic pressure.

Some experiments still in progress in the freezing of water in variously shaped vessels lead the author to believe that the basal plates are placed parallel to the surface of refrigeration, independently of pressure or position of equilibrium. The actual congealing temperature enters quiet water at right angles to this freezing surface, regardless of its position, and each successive plane of molecules in turn feels the effect of the crystallizing force. The result is that sheets of molecules are successively frozen parallel with the requisite isothermal surface as it slowly works its way into the body of the water. The orientation of the plates is facilitated by the fact that in making the ice crystal the molecules arrange themselves more readily (because of the superior crystallizing force) in the plane of the secondary axes than in the direction of the principal axis. This is shown by the form of the snowflake which has been produced supposedly under conditions in which the crystal was free to grow in any direction, so far as the supply of moisture and suitable temperature are concerned. As is well known the molecules are arranged mainly about the short main axis in the plane of the secondary axes. The principle is illustrated further by the frost crystals which form upon the window-pane, with cold air upon one side and a relatively warm, moist atmosphere upon the other. At first only a very thin layer of moisture, parallel with the surface of the glass, can congeal, and in this layer the molecules at once arrange themselves in the plane of the secondary axes. As the atmosphere supplying the moisture becomes cooled for some distance back from the glass the crystals may grow more or less irregularly. That the cohesive force in the ice crystal is much more powerful in the direction of the basal planes than in the direction of the principal axis, is demonstrated in the experiments to be noted later (p. 130). Pressures in a direction at right angles to the main axis will cause the basal plates to slide over one another, as in a bunch of tickets, but no such shearing action can be secured when the direction of pressure is parallel with this axis. According to the view of the writer the temperature condition for the crystallization of the water is supplied successively parallel to the refrigerating surface, whatever may be its position or form, and the molecules yield to the relatively more powerful forces which are operative in the planes of the secondary axes.

e. Glacial granules. Glacial ice, which has not been subjected to a melting temperature, is firm, solid, and, apparently, homogeneous, except for air bubbles and foreign matter that it may contain. It is brittle, breaks without cleavage, and in quantity, when pure, has a rich blue color by transmitted light. Subjected slowly to a melting temperature there is developed a system of delicate capillary tubes, which form a network throughout all the ice affected, and extend into the body of the glacier a number of feet. These tubes outline the granules, more or less perfectly, of which the entire glacier is composed. These granules are irregular polyhedrons, of variable size, with curved faces which interlock with one another. Ordinarily there are no spaces between them that can be recognized and there is no cementing material to bind the granules together. They are observed to increase in size from the névé to the nose in any particular glacier and there can be no doubt but that the granules formerly in the névé are directly related to those seen in the lower part of the glacier. In the Canadian glaciers studied the largest granules were seen in the basal layers about the nose; the Asulkan, the smallest of the glaciers, having the smallest average granules, and the Yoho, the largest glacier, having the largest average granules. When subjected to considerable melting the capillary tubes become irregular and very thin spaces open between the faces of adjoining granules, allowing the granules eventually to fall apart, or to be easily pulled apart.

Each granule is an incomplete ice crystal, incomplete because its development has been interfered with by the neighboring crystals. Belonging to the hexagonal system of minerals, it has a single main axis, which is also its principal optic axis. In common with all known ice crystals it appears to be made up of a bundle of very thin plates, placed with their flat faces together, the axis standing at right angles to these plates. When the granules have melted apart the very delicate edges of these plates, or more probably sets of these plates, may often be recognized extending as delicate parallel lines about the granule and thus indicating the positions of the planes of the secondary axes. These lines are known as "Forel's stripes." They are referred to by Mügge as the "Translations Streifung," and were regarded by him as due to the partial shearing of the basal planes over one another. They are found, however, in newly forming crystals of ordinary lake or pond ice which have not been subjected to any shearing stress. Within the body of the granule there are seen, at times, circular disks of excessive thinness, with their flat faces perfectly parallel and all at right angles to the optic axis. They are of silvery whiteness and appear like "flattened air bubbles," as they were originally described by Agassiz (plate VI of Atlas, figure 10). These are "Tyndall's melting figures" and are cavities, "*vacuous space*," containing nothing more than water vapor, resulting from the internal contraction of the water, as it changes from its solid to its denser liquid condition.

The melting begins at certain points between the crystalline plates and spreads in a direction parallel to them, instead of across, or through them. The planes of these melting figures are parallel to Forel's stripes, and either feature when seen may be used for orienting the crystal. In addition to the stripes of Forel, there is to be seen a very conspicuous system of parallel ridges and furrows, covering the outside of softened granules, which can have no connection whatever with the crystalline structure. The ridges are either continuous, or consist of a series of regularly placed points, forming a wavy, irregular pattern about the crystal. The appearance suggests that seen upon the inside of one's finger-tips and thumb. It shows itself when the adjacent faces of the granules begin to separate and is due to differential melting at the surface, but it is far from clear what could give rise to such a regularly irregular pattern.

By means of the polariscope it was found that there is a tendency towards the orientation of the granules about the nose of the Victoria, Yoho, and Illecillewaet glaciers, the other two not being tested. The Victoria shows distinct stratification about the oblique front, the Yoho indistinct, and in the case of the Illecillewaet, the stratification about the nose seems to have been completely destroyed. Vertical sections of the ice were prepared, cut crosswise and lengthwise, and these were compared with horizontal sections and oblique sections. It was found that there is a marked tendency to arrange the optic axes of the granules in the basal layers near the nose in a vertical position, from one-fourth to one-third of them being estimated to be so oriented. The cause of this orientation is not yet apparent, but connected, undoubtedly, with the method of growth of the granules themselves. In order to account for the orientation which he found in the Greenland glaciers, Drygalski assumed that the granules were separately melted and refrozen with their axes parallel with the direction of pressure, which he considers at right angles to the strata. If it is true that the direction of pressure determines the position that the crystalline plates will assume, and hence the position of the optic axes, which the writer seriously questions, then the space occupied by a single crystal, which has been completely melted, should contain a large number of radially arranged prisms, each standing at approximately right angles to the portion of the ice surface to which its base is attached. Owing to the law of transmission of forces by a liquid the pressure is equal in all directions whether this pressure arises from the weight of the superincumbent ice, or because of the expansion of the water in the closed cavity just before freezing. Drygalski is in error in supposing that the pressure experienced by the liquified granule is *vertical* only, since, if confined, the water would press outward in *all* directions. In case the position of the refrigerating surface, or surfaces, is the cause of the orientation of the plates, then in the closed cavity occupied by the liquid granule, there should be formed a mass of radially arranged prisms, similar to those observed by the writer upon the Lefroy and by Agassiz upon the Aar. In either case, the cavity should be filled with small radially arranged prisms and not by a single crystal with its axis in a vertical position. This furnishes rather conclusive evidence that granules and blue bands never have existed in a completely liquified condition. That they may have been melted partly upon one face and frozen upon another, or the water derived from one by melting added to another granule, is in harmony with known properties of ice. Pulfrich found that when an ice crystal was pressed against a wet surface of glass and allowed to freeze the water between the ice and plate was incorporated into the crystal, so as to make a homogeneous mass.

Much interest is attached to the methods of granular development, since the more modern theories of glacial movement are more or less dependent thereon. It has been shown by Emden, Drygalski, Crammer and others that when névé granules are made into a water slush, such as might originate from excessive melting, or heavy rainfall, the granules grow in size and, under favorable conditions, quite rapidly. In the névé as well as in the body of the glacier, however, there must be a maximum limit which the granules may attain by this means for the ice will presently become too compact for more water to enter and no space will be left for the growth of individual crystals.[1] That further growth of the granules does not take place by the simple freezing together of neighboring granules, is conclusively shown by the homogeneous structure of the mature granule. That new granules cannot originate by the complete and simultaneous melting of a number of adjacent smaller ones, is believed to have been just shown in the preceding paragraph. Of the various theories of granular growth remaining we may recognize three divisions, based upon evaporation, melting, and "dry union."

First.—It has been shown by Chamberlin and Salisbury that in dry granular snow, kept continually below the freezing temperature, certain granules will grow in size at the expense of the others, presumably by the giving off and congealing of water vapor.[2] In the porous snow of the névé it seems probable that the principle would be operative and that the granules would diminish in numbers and increase in size, even when not immersed in water. For the body of the glacier, with the granules in such intimate contact, the authors do not believe that evaporation and condensation can take place to any appreciable extent.

Second.—Making use of the principle of Thompson that ice may be melted by pressure, without any change in temperature, many investigators, as Mügge, Drygalski, Chamberlin, Crammer, etc., have accounted for the growth of the granules in the main body of the glacier by assuming a partial or complete melting and refreezing. Those granules which owing to their location are subjected to the greatest pressure, or internal friction, or those portions of granules similarly affected will melt, thus redistributing the pressure and allowing the free molecules to attach themselves to the most favorably located granules. The liquefaction of the granules may be confined to their outer surfaces, or, as Drygalski believes, take place locally in the bodies of the granules. Chamberlin believes that the granules

[1] See Hagenbach-Bischoff's criticism of Forel's infiltration theory, "Weiteres über Gletschereis," *Verhandlungen der Naturforschenden Gesellschaft in Basel*, VIII, 1889, p. 822.

[2] *Geology*, vol. I, Chamberlin and Salisbury, p. 296 (Chamberlin, Peet, and Perisho). "A Contribution to the Theory of Glacial Motion," Chamberlin, Decennial Publications of the Univ. of Chicago, vol. IX, p. 194.

are subjected to more or less of a rotary movement and a sliding along their limiting surfaces, by which the internal stresses of the glacier are undergoing constant readjustment and the ice mass permitted to move under the influence of gravity. These views of granular growth would call for constant changes in the form, size, and number of the granules and in their relative position.

If the principles underlying these views—melting under pressure or friction—were alone operative in granular growth there should occur a much larger number of smaller granules mingled with the larger in the basal layers about the nose of a glacier. Owing to the manner in which the granules are keyed together the strain upon the smaller would be relieved as they diminished in size and would be transferred to the faces of the larger neighbors. Lying in between the coarser granules we should expect a considerable number of these smaller remnants, but such occur only somewhat sparingly. The remarkably well preserved blue bands in the basal layers about the nose of the glacier furnish conclusive evidence it seems to the writer that the granules have not been destroyed since the bands were produced and that they have not materially shifted their position with reference to their neighbors. Upon the surface of the lower Asulkan Glacier these bands were found so thin that thirty were included within the distance of four inches, several necessarily cutting across adjacent granules. Any perceptible shifting of the granules as the result of sliding or rotation would give rise to faulting of these bands, while their destruction by either slow or rapid melting would cause abrupt gaps in the continuity of these bands. The preservation of the depositional laminæ from the névé to the nose would seem impossible if the granules are being destroyed and reformed or rotated out of their original position with respect to their neighbors.

Third.—The "dry union" of granules described on page 40 of this report accounts for the reduction in the number and an increase in their size toward the nose of the glacier. According to this theory the molecules of the yielding granule give up their own crystalline arrangement and without any apparent melting are immediately incorporated into the body of the controlling granule. Heim's view was that such a union could occur only when the main axes of the two granules were placed in approximately parallel positions,[1] but the experiments of Hagenbach-Bischoff showed that such union could occur regardless of the position of the axes,[2] and this he regarded as the true cause of granular growth in the glacier. This view was accepted by Emden in his prize essay, "Ueber das Gletscherkorn," published in 1890. It furnishes the simplest theory of granular growth, not of glacial motion; accounts for whatever uniformity exists in the size of the granules, calls for no shifting of the granule relative to its neighbors, and hence permits the continuity of laminæ and blue bands.

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[1] *Handbuch der Gletscherkunde*, 1885, s. 330.

[2] *Verhandlungen der Naturforschenden Gesellschaft in Basel.* Bd. vii, 1888, s. 192; Bd. viii., 1889, s. 635 und 821. *Archives des Sciences physiques et naturelles*, T. xxiii., 1890, p. 373.

8. Theories of Glacial Motion.

The one question that continually arises in the minds of all glacial students, with tantalizing frequency is—what is the nature of this glacial motion? Are we any nearer an acceptable hypothesis than we were nearly seventy years ago when the serious study of glaciers was begun? Possibly! Without attempting the discussion here of the various theories that have been proposed, the writer desires to record his convictions after his Pleistocene studies in the Lake Erie region and his four consecutive seasons about the Canadian glaciers. All are now agreed that sliding, expansion by freezing or changes in temperature, general melting under pressure and regelation cannot fully and completely account for the known facts of glacial motion. Probably all will admit that, under certain circumstances, every one of these factors may find its application. In the névé region it is possible that a certain amount of rolling and sliding may occur amongst the granules, producing some motion, such as we may see in a pile of beans or peas. Farther down in the glacier, although the granules are intimately interlocked, it is quite probable that they would permit of a certain amount, possibly considerable, motion between their adjacent faces. If we introduce the idea of a partial melting of the granules, those portions of them subjected to especial stress, or friction, will yield under the action of gravity working from above, or behind, and will permit other granules to yield. Upon relief of pressure, the water will be frozen to the original granule or distributed to neighboring granules, as discussed in the preceding paragraph, and thus the movement of the glacier may arise entirely from the alteration and growth of its component granules. We must assume that the heat necessary for the partial liquefaction of the granules is developed within the glacier as the result of pressure and friction and not that it is derived from the atmosphere, or the bed.[1] However, any heat communicated from such a source will make it that much easier for internal changes to take place. As presented by Chamberlin and Salisbury, this theory of granular change accounts more satisfactorily for the glacial phenomena observed than any other, in which no molecular movement of the solid granules is assumed.

The original idea of plasticity ascribed to glaciers by Rendu and developed by Forbes is based upon the conception that the molecules of firm ice will yield continuously to a stress, without producing visible rupture. The stress may be of the nature of a thrust, or of tension. This theory has been rejected by the most prominent physicists who have turned their attention to the problem of glacial motion, because of their unwillingness to admit that ice could possess this and certain other properties apparently inconsistent with plasticity. The difficulty so far as rigidity alone is concerned is removed by our knowledge that such substances as lead, tin, and iron may be made to flow by pressure, under ordinary temperatures. As soon as direct experiments were made to test the plasticity of ice it

[1] In a recent pamphlet entitled, "The Viscous *vs.* the Granular Theory of Glacial Motion," Mr. O. W. Willcox has endeavored to show that the heat developed through pressure or impact of the granules would be conducted away as rapidly as it is generated (p. 18).

was found that bars of ice frozen in a mould, or cut from a glacier, may be bent, elongated, compressed, and twisted, without visible rupture, even when kept continuously below the freezing temperature. These experiments were made by Main, McConnel, Kock, and Mügge and show that solid ice, made up of a collection of irregular crystals, is decidedly plastic. McConnel calculated that the amount of extension required of the ice in the Rhone Glacier, because of the more rapid central movement when compared with its sides, amounted to 0.0029 millimeter per hour, for each 10 centimeters of length. In his experiments with bars of glacial ice, but one of the three bars tested showed as small amount as this and that for only a portion of the experiment. In the case of single crystals they were found capable of continuous yielding without rupture, providing the pressure was applied at right angles to the optic axis, the movement appearing to consist of a sliding between adjacent crystalline plates. When the force of compression, or tension, was applied parallel with the axis, the result was exceedingly small, or *nil*.[1] The verification of these results by other investigators leads to the conclusion that ice is capable of showing a certain type of plasticity, although different from that ascribed to it by Rendu and Forbes. An amorphous plastic substance yields under a suitable stress in any direction without visible rupture. A crystalline substance which maintains its definite molecular arrangement will be limited in the number of directions in which it may yield. If ice crystallized in cubes it seems likely that it might have yielded without rupture in three directions. Had it crystallized in square prisms we may now conceive of a movement in two directions. In the hexagonal system in which it actually crystallizes the molecular cohesion measured in the direction of the main axis is of a sufficiently different nature from that at right angles to it to permit of a gliding of the basal plates without rupture and the destruction of their molecular arrangement. *This is plasticity in a crystalline substance.* The experimental results were obtained with moderate stresses and much below the freezing temperature. In the case of a glacier under great stress and a temperature near the freezing point it seems absolutely necessary that the glacial granules should manifest this property to a greater or less extent, regardless of the actual mechanics of glacial movement.

A number of phenomena, noted upon the Canadian glaciers, has convinced the writer that a certain amount and kind of plasticity is a fundamental property of glacial ice. The complicated patterns occasionally shown by the blue bands are such as might arise from plasticity, but not from melting or rotating of the granules. When similar effects are seen in ordinary rocks they are commonly referred back to a plastic condition of the matrix. It was noted that when the difference in the rate of movement between the centre and margins of the glacier is sufficiently small, there are no marginal crevasses to be seen. This implies that the ice permits a certain amount of stretching, without visible rupture. If ice were absolutely incapable of yielding under tension, any appreciable difference be-

[1] "On the Plasticity of Glacier and other Ice," James C. McConnel, *Proc. Roy. Soc. of London*, vol. 44, 1888, p. 331; "On the Plasticity of an Ice Crystal," vol. 49, 1891, p. 323.

tween the rate of movement of center and sides must open marginal crevasses. In the rock scorings seen near the nose of the Illecillewaet, the frontal and lateral grooves about the knobs and trails suggest very strongly a plastic condition of the ice. In the case of the same glacier, but farther up between the ice and the left lateral moraine, the ice was seen moving over a knob of bedrock not fully exposed in 1904. Transverse crevasses formed above while the ice melted below and there were formed strips of ice, 20 to 25 feet long, supported at either end. Moving downward these strips were suspended in the air, and in the course of ten days in September one bar had sagged so as to be very noticeable to the eye, without forming any crevasse large enough to be noticed, or to permit of the destruction of the ice bar itself. This phenomenon seemed to indicate that the ice could, to some extent, yield to a tensional stress.

Now that the question of the plasticity of granular ice has been settled by experiment, what objections are there that may be urged against its application to the glaciers? Crevasses and faultings indicate simply that there is a limit to its plasticity, as indeed there is to the most typically plastic solid. The *tendency* to flow must be greater in the basal layers, but it does not necessarily follow that with the friction of the bed to combat, the velocity here will be greater than or even equal to that of the upper layers. The hold which glaciers have upon rocks in their basal layers is probably not a firm one. It seems to the writer that the chatter-marks, crescentic gouges, the shape and often sudden termination of the coarse striæ, as well as the faceted condition of the boulders in the ground moraine, all indicate that the glacier was persistent, rather than firm, and that it very often lost its grip. All of the phenomena of rock scoring, the subglacial fluting of the ice, the compression of the ice at the base of a slope, the phenomenon of shearing, and the mounting of reversed slopes prove that portions of the ice move bodily under the influence of a more or less rigid thrust from behind. This necessary amount of rigidity in the ice is not inconsistent with the degree of plasticity ascribed to it. When the flow is not sufficiently rapid at any point the ice must be thrust forward bodily. The most forcible argument against this modification of the viscous theory of glacial movement is brought forward by Chamberlin. It would seem that the granules should be distorted noticeably in the direction of flow. That this distortion is not more apparent may be due to the complete mechanism of granular growth. It may be disguised by the shearing of the granules in the direction of the basal planes and their later dry union by the principle of Hagenbach-Bischoff.

9. Color of Ice and Glacial Water.

The exquisite richness and variety of coloring seen in glaciers and glacial lakes constantly arouses the wonder and admiration of those privileged to gaze upon them. The colored photograph fails to reproduce it and it eludes the brush of even the most skilful artist. An explanation of the cause of this coloration can scarcely fail to be of interest. In 1904 a study was made of several of the lakes by means of standard solutions of copper and nickel sulphate and an instrument devised from a stereoscope. By using measured amounts of the solutions and mixing with pure water it was possible to match the water and to express its color as an equation, from which the depth and shade of color might be at any time reproduced. The solutions were prepared by dissolving 30 grams of the chemically pure salt in 100 cubic centimeters of distilled water and were placed in a thin glass "cell," with parallel sides, the inside measure of which was 8 millimeters. A reflector was so arranged that the water could be viewed directly, while the fluid mixture was seen by reflected diffused light. The proper proportions could then be obtained by experiment. The shade of color changed somewhat by the condition of the sky, the position of the observer, the time of day, and the strength of the wind. In the case of Moraine Lake the depth of blue was too intense in the quiet of the early morning to be matched by the pure copper sulphate solution, in a cell of the above thickness. A slight breeze sprang up and lightened the shade sufficiently. The table below gives the color simply at the time of observation and under the conditions then prevailing.

COLOR OBSERVATIONS UPON ROCKY MOUNTAIN LAKES.

Lake.	Date.	Time.	Proportions in cubic centimeters.	Sky.
Lake Louise	Aug. 3.	8:45 A.M.	29 c.c. green + 10 c.c. blue + 65 c.c. water.	Clear but hazy.
Emerald Lake	Aug. 16.	8:00 A.M.	10 c.c. green + 10 c.c. blue + 50 c.c. water.	Fair.
Moraine Lake	Aug. 10.	10:00 A.M.	3 c.c. green + 30 c.c. blue + 23 c.c. water.	Sunny.

As the season advances a marked change occurs in the color of the water of Lake Louise, there being much more blue in the lake in the early part of the summer and more green towards the fall. Mr. Robert Campbell informed me that a decided change has occurred in the color of the water of Emerald Lake in the last few years, it being more of an emerald when he first saw it and now he considers it more of a turquoise. In discussing this change with Mr. Bell-Smith, the Canadian artist, I learned that he had observed the same change since 1888, there being a very noticeable increase in the amount of blue.

Some simple observations and experiments in the field made clear to the writer the cause of the differences in color of the water of different lakes and the changes that occur in the same lake. It had been remarked before, but it was left for Bunsen to demonstrate that absolutely pure water is blue, as seen by transmitted light.[1] The colors with the longer wave-lengths, as yellow, orange,

[1] "Ueber den innern Zusammenhang der pseudovulkanischen Erscheinungen Islands," *Annalen der Chemie und Pharmacie*, Bd. LXII, 1847, p. 1. Previous to the time of Bunsen the illustrious scientists, Newton Humboldt, Davy, Arago, and Forbes had speculated upon the problem but with only meager results. Later Beetz, Tyndall, Bezold, Boas, and Aitkin had more or less completely grasped the idea of *selective absorption* and gave us a satisfactory theory of the various modifications of the color of water in nature.

"Ueber die Farbe des Wassers," von W. Beetz, *Annalen der Physik und Chemie*, Bd. CXV, 1862, s. 137 zu 147.

The Glaciers of the Alps, chapter 6, Pt. II, Color of Water and Ice, 1860, Tyndall.

Lectures on Light, Tyndall, 1877, p. 35.

Theory of Color, Wilhelm Von Bezold. Translated by Koehler, 1876, pp. 41 and 67.

"On the Color of the Mediterranean and Other Waters," Aitkin, *Proc. Roy. Soc. of Edinburgh*, XI, 1882 pp. 473 to 483.

and red, are absorbed if passed through water of sufficient thickness. While of the colors at the other end of the spectrum, with the short wave-lengths, blue is the one which water is chiefly able to transmit, violet and green being also transmitted, but less perfectly. Bodies of pure water of a volume sufficient to absorb the longer waves of light reflected from the bottom, but not so deep as to absorb it all, will appear blue. This blue is not reflected from the sky, although the condition of the sky will affect the tint. Lakelets in the névé, such as the one discovered upon Sapphire Col by Mr. Wheeler, are a rich blue; those upon the ice may be blue, or not, depending upon their freedom from sediment, being liable to change rapidly. Moraine Lake (plate xxv) owes its exquisite blue color to its purity and depth. Water in the form of ice possesses still the same power to transmit the colors with the shorter wave-lengths, violet, indigo, blue and green, with the preference for blue. If a mixture of these four colors, or of all the others which compound white light, be passed through a block of pure ice, of sufficient thickness, none but the blue will emerge. If no light whatever is being transmitted through either ice, or water, it will look black, or will show whatever color of light is being reflected from its surface.

From this blue as the fundamental and natural color of ice and water by transmitted light we meet with many modifications in nature. Finely divided ice, as snow and névé, presents innumerable reflecting surfaces from which light of any and all colors is sent to the eye. The same is true of water lashed into foam, or in any finely divided state, as fog, cloud or condensed steam. In ordinary light these forms of water and ice appear white, but in the gorgeous colors of the sunrise and sunsets they transmit to the eye by reflection the greatest variety of color. Névé begins to show a bluish tinge as soon as the transmitted light begins to predominate over that which is being reflected. The water which issues from the glacier is generally charged with sediment, and if this is much in amount, its color will determine the color of the water of the drainage brook. It generally appears a milky, or creamy, white but may be a dirty gray. With the deposition of the coarser yellowish sediment and the retention of the very finest, if the volume of water is considerable, the water assumes a greenish tinge, as seen in the Asulkan and Illecillewaet streams. With the loss of this sediment the stream acquires more and more of its natural blue. When this glacial sediment is introduced into a lake in sufficient, but not too great, quantity the water becomes charged with finely divided rock particles in suspension. These particles are able to reflect the longer waves of the spectrum, particularly yellow, but also the closely related green and orange, while they very effectually cut out the shorter wave-lengths giving rise to violet, indigo, and blue. The result is that there are introduced into the water innumerable reflecting faces which are capable of sending to the eye only those colors that lie at the centre of the spectrum and towards the red end. But the only light that is available for reflection is that which has already passed through the water once and had its yellow, orange, and red to a greater or less extent filtered out. That which remains to be reflected by the foreign particles will pass again through the water and will suffer still further absorption. Of the blue and green rays, which make their way readily through the water, only the green rays are reflected by the particles and these alone reach the eye. The quantity of light is thus much reduced in amount, but with the sun shining upon the lake the green becomes quite vivid if the water carries the requisite amount and kind of foreign particles. If the foreign particles were pure white they would be capable of reflecting all colors equally well, and the rich blue of the water would be brought out in perfection.

In the case of Lake Louise, we have a variable amount of sediment entering the lake during the year, and consequently a seasonal variation in the color of its water. With the very slack drainage during the winter, the sediment, in considerable part, settles and the water in the spring shows more of its own blue color. With the increased activity and melting of the Victoria Glacier the supply of sediment delivered to the glacier increases as the summer advances and the water becomes a richer and richer green. About the delta at the head of the lake the sediment is so abundant and lies so near the surface that the water is unable to absorb the yellow, and the color of the sediment itself is seen with little or no modification. In the case of the change in color noted for Emerald Lake we may infer that the drainage stream at its head has been carrying less sediment than formerly. It is not improbable that the diminished activity of the inlet may be connected with the stage of diminished precipitation recently closed and that the rich emerald green of the lake in 1888 and earlier was connected with the stage of increased precipitation, which is supposed to have closed in the early 80's. With an increase now in the average annual precipitation it will be interesting to see whether the lake returns to its former shade of color.

The introduction of green or yellow, organic solid matter, animal or vegetable, into the body of water would have the same effect. If the lake is sufficiently shallow and the bottom covered with green vegetation, or yellow sediment, the water will not be able in the short transmission to cut out the green and this color may appear in lakes of water free from sediment. About the margin of Moraine Lake the water has a greenish cast for this reason. Organic matters in solution quite generally give water a yellowish to brownish color, as seen naturally in bogs and artificially in tea, coffee, cider, beer, etc. With the above principles in mind one may infer from a glimpse of a distant lake the condition of the water and the state of activity of glaciers whose drainage streams empty into it. If upon rounding the shoulder of Mt. Temple, in entering the Valley of Ten Peaks, the first glimpse of Moraine Lake showed that a rich green had been substituted for its superb blue, one might safely infer that the Wenkchemna Glacier had begun to erode its bed although a neighboring rock slide might temporarily give such a result. Even the names of lakes in a glacial region are suggestive of the amount of glacial activity in the valley, such as Sapphire Lake, Turquoise Lake, and Emerald Lake.

The same principles of coloring apply to ice as well as to water. When highly charged with sediment of any particular color, its own natural color is obscured and the color of the sediment is sent to the eye with little or no modification.

If, however, yellowish sediment is distributed through the ice in proper proportions the case is identical with that discussed for water, and the ice assumes a greenish cast. In the case of the solid ice the sediment can not be assorted and evenly distributed as in the case of water and hence only greenish patches and streaks occur, just where conditions are favorable. It has not seemed appropriate to any one to apply the names "emerald," or "turquoise," to a glacier while "sapphire" would not be very distinctive. By applying the principles here set forth we may account for the coloration of glaciers, the lakes in their neighborhood; the gorgeous pools of blue and green water in the Yellowstone Park and similar regions, the blue color of the ocean and the seas, the green and final yellow strip as we approach the shore and such phenomena as the blue and green grottoes of the island of Capri. No one has yet satisfactorily explained how a considerable body of pure water may appear limpid.

THE END.