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ON THE MECHANISM OF ELECTRICITY GENERATICN IN THUNDERSTORMS

[REVIEW PAPER]

by

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[USSR]

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NATURE OF AEROSOL PARTICLE CHARGING

Works on atmosphere electricity, carried out during IGY, including the time periods before and after it, allow to derive a series of conclusions as to the nature of thunderstorm electricity.

In the work [1] the author has shown that electric charges, whose sign depends on the acid or alcaline properties (pH) of the atomized solution, are formed on particles of stationary or slowly evaporating aerosol. If the pH of the moisture, of which aerosol particles are formed, is greater than 5, positive charges are formed on particles, and when pH < 5, these charges are negative. This phenomenon is explained by water dissociation into H^+ and OH^- ions and by selective sorption of these ions by aerosol moisture. The charge, then forming on aerosol particles, constitutes several tens of elementary charges. The electric potential of particles relative to air reaches 20 — 30 MW.

These results allowed the author to derive a theory of origin of the Earth's normal electric field [2]. The latter is explained by gravitational settling of positively charged aerosol in negatively charged gas that surrounds the terrestrial glove. The negative charge of the Earth is formed by transfer to Earth of air particles with negative charge due to its conductance. This is a further development of the idea of colloid electricity application to atmospheric electricity events, first postulated by Frenkel' [5].

* O MEKHANIZME GENERIROVANIYA GROZOVOGO ELEKTRICHESTVA.

** The periodical, where the present paper was published could not be ascertained, but, it is evidently in the cateogry of IGY series, not published by the USSR Academy of Sciences, but by some regional agency or institute, in the years posterior to 1962.

Imyanitov and Chubarina [3] have shown that, judging from the results of measurements during IGY, the widely spread theory of electric field of the Earth, known as theory of spherical condenser, failed to find corroboration. They reached the conclusion that it is more appropriate to pass to the model of a charged sphere, surrounded by a space charge.

While considering the possibility of cloud drop charging owing to selective sorption of ions of various salts, Nikandrov indicated [6] that the excess of ions of one sign in the superficial layer should lead to their evaporation alongside with water molecules.

Muleisen [4] has shown that the sign of the drop charge in artificial and natural aerosols depends upon, whether or not, condensation and growth of particles or their evaporation take place : in the first case a negative charge forms on particles, in the second case — a positive one is generated. Muleisen brings forth the assumption, that the cause of this resides in the liberation of negative ions from the surface of the water during evaporation. These ions are captured by condensation nuclei and form a negative charge; at fog evaporation the negative ions are liberated again and carried by the electric field.

The mechanism of aerosol particle charging was the object of a conclusion in the work [1], derived on the basis of the works by Muleisen [4] and Nikandrova [6]. It may be made more precise in the following manner.

Starting from the principle of selective adsorption of ions H^+ and OH^- by water, and assuming that the concentration of hydrogen ions, being more adsorbent, increases in depth of the droplet (whereas at periphery mostly OH^- ions are concentrated), we may write after the Boltzmann law [1] :

$$[H^+]_{\text{в}} = [H^+]_{\text{п}} e^{\frac{W}{RT}}, \qquad (1)$$

where $[H^+]_{\text{в}}$ and $[H^+]_{\text{п}}$ are respectively the concentrations of hydrogen ions inside and on the surface of the droplet.

The processes of condensation, evaporation or stationary state may be characterized by the number of water vapor molecules, outgoing into the air from the surface of the drop $n_{\text{ж}}$, and the number of vapor molecules $n_{\text{ж}}$, settling on it out of the moist air.

The drop will have a zero potential relative to air only when

$$n_{и}[H^+]_{н} = n_{к}[H^+]_{в}. \qquad (2)$$

Assume, that at significantly remote distant from the drop

$$[H^+]_{\infty} = [OH^-]_{\infty} = 10^{-7}. \qquad (3)$$

This means, that there exists near the surface of the drop an increased concentration of ions (OH^-), described by the correlation

$$[OH^-]_{н} = [OH^-]_{\infty} e^{\frac{W}{RT}}. \qquad (4)$$

Factually, this correlation is disrupted by the turbulent diffusion of ions OH^- from the boundary layer to air, free from the action of superficial forces of aerosol particles. Bearing in mind that $\lg[H^+] = -pH$, we obtain from (1), (2) and (3) an equation describing the condition of neutrality of the drop or of the aerosol particle

$$pH_0 = 7 - \frac{W}{2{,}3RT} + \lg\frac{n_{к}}{n_{и}}. \qquad (5)$$

Therefore, the sign of the charge of a drop depends not only on acid or alcaline properties of the solution forming it, but also on whether or not there take place on the drop either condensation or evaporation.

In Fig. 1 we reproduced the curve of the electrokinetic potential of the drop and its charge (counting on drop's radius of 5 mk) dependence pH, forming the solution's drop, obtained by the author by empirical method in stable or slowly-evaporating aerosol (curve a). Plotted in the same figure is the curve б for the case of intense condensation and the curve в for the case of violent evaporation. The curves б and в were obtained by shifting the experimental curve according to equation (3). At the same time, we took for the example of condensation $\lg\frac{n_{к}}{n_{и}} = 2$, and for evaporation $\lg\frac{n_{к}}{n_{и}} = 1$. It may be seen in the figure that the drops of solutions of same acidity, for example with pH = 5 to 6, will have a different potential relative to air at condensation and evaporation processes. In the stationary state the charge of the drop at such pH will be positive or near zero; at condensation such a drop will have a negative potential and charge relative to air; at evaporation they will be positive.

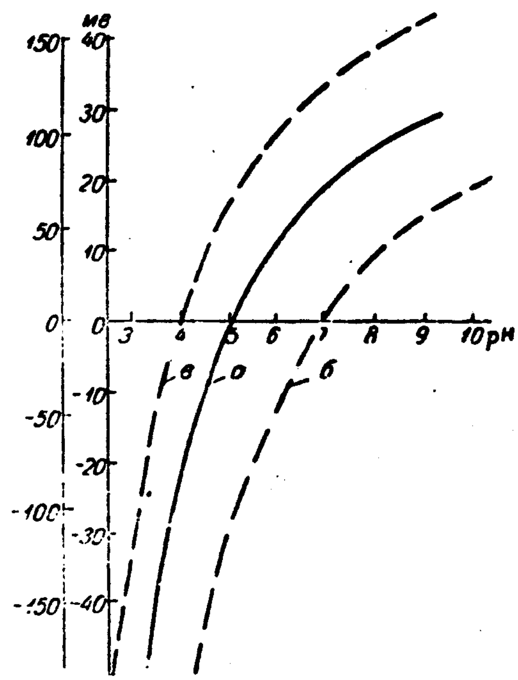

Fig. 1. - Dependence of the electrokinetic potential at the surface of aerosol particles (of the cloud) on acid or alcaline properties of moisture, condensation and evaporation processes, forming them.

a — state of equilibrium or stage of slow evaporation;
δ — intensive condensation; в — intensive evaporation.

Let us recall, that the moisture of falling out precipitations has an average pH of 5 — 6 [2]. Assuming for a moist air the prevalence of ions OH^- over ions H^+, which is regular since $\lambda_- > \lambda_+$ [19, 20], instead of $[OH^-]_\infty = 10^{-7}$ we may take, for example, $[OH^-]_\infty \sim m \cdot 10_{-7}$, where $m > 1$. Then, in the right hand part of the equation (3), the first term will be somewhat greater than 7 (for example, at m = 2 it will be equal to 7.2). This does not virtually introduce any changes in Fig. 1.

A series of works appeared during IGY, which corroborate one way or another the above-discussed mechanism of charge formation on cloud drops and aerosol particles. Thus, Blanchard [21] ascertained, while investigating the charges of drops forming during rupture of air bubbles passing through sea water, that the tiniest spray is charged positively. It is well known, that sea water has an alcaline reaction with pH near 9, that is, ions OH^- are in excess in it. The primary ion OH^- desorption from the evaporating sea wave spray leads to positive charging of the then formed tiniest droplets and particles of aerosol. Therefore, the ocean is apparently the main supplier of positively charged atmospheric aerosol. The negative ions OH^-, liberated from the surface of such an aerosol, increase the negative charge of the air. Part of such a charge is yielded to terrestrial surface. Thus forms the negative charge of the Earth. In the unitary wave of the daily course of atmosphere's electric field the maximum occurs near 1500 – 2000 hours GMT, when the greatest part of the universal ocean is lit by the Sun [2].

Kuettner and Lavoil [23], while studying the mechanism of aircraft electrization, had set up the experiment, whereby the sampler, in the form of icy grating was exposed in a screening cylinder beyond the window of the mountain observatory tower. In clear weather a positive charge occurred in 100% of cases on the surface of the sampler. During mist with drifting snow, that is when the observed conditions were favorable for sublimation (condensation), a negative charge appeared on the sampler.

These experiments corroborate also the above-described mechanism of electrokinetic potential emergence and charge subdivision at water-air boundary on account of spontaneous water dissociation and selective sorption and desorption of the then emerging ions H^+ and OH^-, different in conditions of evaporation or condensation.

According to data on electric field measurement under clouds and above them on the slopes of Elburs, Krasnogorskaya [9] has established that in their initial development stage clouds have a negative space charge. According to Pudovkina, the same clouds acquire a positive charge when passing from generation to stationary state and also in the state of breakdown.

Krasnogorskaya assumes [9], that the adsorption mechanism of charged particles during the initial stage of cloud development plays a specific role in the formation of negative space charge; this adsorption mechanism being based upon the property of water drops to adsorb mostly negative ions.

Summing up the above data, one may note that during condensation processes, aerosol particles or the forming cloud droplets acquire a negative charge, but at evaporation or in the stationary state they acquire a positive charge, provided their reaction is not too acid ($pH > 5$). The selective desorption (or adsorption) of ions OH^- and H^+ appears to be the cause of this phenomenon. By the strength of selective sorption of these ions, mostly ions OH^- are concentrated on the surface of aerosol particles. At evaporation they break away alongside with vapor molecules and outgo in the air. This leads precisely to positive charging of aerosol particles (droplets) in the stationary or evaporation stage.

When violent condensation onsets, water vapor settles on condensation nuclei (aerosol particles), which has mostly negative ions OH^-. At the same time there are formed embryonic negatively charged droplets. Apparently, the cause of preferential settling of vapor molecule complexes containing ions OH^- on the surface of embryonic droplets or aerosol particles at condensation, consists not only in their relative excess in the air, but also in that these particles have, by the strength of great mass, a great micellar force potential, contrary to ions containing H^+. Their "condensation point" is thus lower than that of the ion complexes containing H^+. Therefore, the energy of charge division between water and gas-like aerosol medium and, in the last resort, the energy of formation of localized charges in clouds are drawn out from adsorption and condensation heat. Taking the value of condensation heat equal to 600 cal/g for a 5 g/m^3 cloud water content, we shall obtain the heat energy of condensation, liberated (or stored) in 1 km^3, equal to $3 \cdot 10^9$ k cal or $1.25 \cdot 10^{10}$ k.joules. The energy density of electric fields in thunderclouds for their usual field intensity near 100 v/cm is $4.5 \cdot 10^4$ k joule/km^3, and at high intensity of 10 000 v/cm it reaches $4.5 \cdot 10^6$ k joule /km^3. Therefore the transformation of a small part, no more than 0.0004 – 0.04 % of thermal energy of condensation and selective adsorption into energy of electric charge separation at boundary water - air, is sufficient for the explanation of atmosphere's electric field energy.

GENERATION OF CHARGES IN A THUNDERCLOUD

Contemporary observations corroborate the distribution of charges in a thundercloud given in the Simpson and associate ref. [10] scheme.

Thus, Tamura [24] established on the basis of synchronous measurements of the electric field in thunderclouds from 8 points, that in thunderstorms the centers of negative charges, inducing discharges from cloud to ground, are at heights from 6 to 8 km, while the centers of positive charges are by 5 to 6 km higher, that is at about 12 km height level.

Fitzgerald and Byers [25] established, while conducting convective cloud observations from aircraft, that the electric structure of cumulus clouds corresponds to ascending current (updraft) structure and reminds one of "charged columns". At the same time it was revealed that in regions with great content of droplet moisture and strong updrafts, excess negative charges are observed in the stages of active development of a powerful cumulus cloud. The solid precipitations, including the lines of fall from anvil-shaped thunderclouds have, immediately upon formation, a positive charge. It was noted, that the field intensity in clouds increases with the latter's water content.

Chapman [26] made more precise the methods of computations and the data of Simpson et al on measurement of electric fields in thunderclouds. The improved values of mean field intensity in thunderclouds were found to be near 10^3 v/cm.

Hatakeyama [27], while admitting that the positive charge is at 10 km height and the negative one at 6 km, and measuring the rapid fluctuations of the electric field at lightning discharges, has established that, as an average, a charge of one sign in a thundercloud is equal to 90 k and reaches up to 400 k.

According to Norinder data [10], the predominating number of lightning discharges transfer charges of nearly 2 k, but there occur discharges, transferring up to 35 k. At the same time discharges to ground from negatively charged part of the cloud constitute 93% of all lightning strokes on ground. The usual duration of a discharge is within the 100—200 μsec range. The strength of the current in vertical lightning is predominantly below 20 ka, but there occur discharges with currents to 140 ka. The time of current accretion to half the optimum value is about 6 μ sec. Calculation by Norinder show, that if the disposition of the space charge in the cloud is represented in the form of an ellipsoid, a field strength near 25 kv/cm will be necessary to initiate a lightning stroke toward Earth at the lower end of the ellipsoid, situated at the height of 2 km above ground. At the same time, a field intensity near 3.5 kv/cm is observed.

Smith [28] found, while investigating electric fields in Florida thunderstorms, that most of the observed discharges took place inside the clouds. At the same time in 95% of cases, the positive charge was situated above the negative one. The frequency of discharges at the center of thunderstorm activity constituted as an average one stroke every two minutes. He noted that the restoration of the field at downpours took place very rapidly, and assumed that here the effect of droplet sprinkling was manifest.

Vonnegut and Moore [29], while describing the electric storms taking place in tornado regions, pointed out that the gigantic thundercloud of a tornado spreads in height to 20 km, the updraft velocities attaining 100 m/sec. The lightning at the center of the funnel hits continually, while at periphery of the tornado, sounds are observed, reminding one of a powerful humming, which apparently is the consequence of glow-discharge.

When studying the position of the lower seat of the positive discharge in a thunderstorm, Williams [30] found that the seat is mainly situated ahead of the rainy zone and has 1 km in height and width. For a series of storms of width near 10 km, he established that the discharges to ground took place in a narrow zone of most intense precipitations, of about 2 km in width, moving together with the cloud.

Very interesting results were obtained by Atlas [31] during radar observations of lightning discharges. To that effect he utilized a powerful radar with a 10.7 cm wavelength with a sounding pulse duration of 2 μsec and 5 Mw power. Because of the concealing reflecting signal from precipitations he could mainly observe lightnings above 5 km. He established that lightning reflections begin, as a rule, above reflections from precipitations and namely from a height of 14 – 15 km. The discharges in the upper part of the cloud have a shape of vertical streamers, widening downward. Observed also are reflections from large volumes, being apparently regions of continuous ionization in the upper parts of clouds or above them. Discharges of great vertical extension are seldom observed, while those of small extension are very frequent.

Chuvayev and Imyanitov [11] have established that the intensity of of the electric field of a powerful cumulus cloud rises sharply at the moment of time when a bright spot appears on the radar screen from the region of large-size particles emerging in the cloud. It is possible that the transfer of water from liquid to solid state is attended by a certain variation of the electrokinetic potential at the boundary ice-air, which would be an explanation of the authors' opinion that the rise of electric field intensity is caused by the appearance in the supercooled summits of the clouds of ice particles. But the question of the possibility of generating significant charges at transition of water from liquid to solid state has not, so far, been fully studied.

Moreover, well known are the facts of large thunderstorm fields, of discharges in the form of summer lightnings and lightnings, even in powerful cumulus clouds devoid of iced summits and precipitation zone, for example of the so called dry thunderstorms.

Thus, Moore, Vonnegut and Botka [32] point to the appearance of significant electric fields in powerful cumulus clouds prior to detection of radar reflections from precipitations. At the same time, the intensity of the field in the cloud is found to be greater than under it. In the lower part of the cloud, which is completely free from the icy phase, great negative charges are formed. The authors note that this negative charge increases with the rise of cloud's height. At lowering of the "tower" the charge disappeared and the field intensity under the cloud acquired normal values.

Therefore, the mechanism of generation and separation of charges begins to act from the time of thundercloud development and still prior to its summit's icing, but reaches its maximum only in a period of distinct thunderstorm activity. This leads us to think that the electrization of cloud elements does not take place on account of the causes assumed in the Simpson and associate theory, but is due to the action of other factors. One of such factors can be the effect of cloud drop electrization under the action of cloud moisture partial dissociation on ions and of selective adsorption (desorption) of these ions at the surface of cloud particles.

STAGES OF A THUNDERSTORM

Prethunderstorm Stage of the Cloud. As follows from the data brought up in Fig. 1, there emerges at the boundary water droplet — air at moisture's pH near 5 — 6, usual for atmospheric aerosol, an electrokinetic potential of several millivolts, apparently not higher than 10 mv, which conditions the appearance on droplets of ~ 5 mk radius, up to 10 - 20 elementary charges. At usual content of some 100 — 300 droplets per cm^3 of cloud volume this leads to the appearance of a space charge near $1 \cdot 10^3 — 6 \cdot 10^3$ elementary charges in $1\,cm^3$. Such order of space charge density was also obtained by Muleisen during his experiments [4] in the condensation processes in laboratory conditions as well as at field experiments with fogs. During violent condensation in an ascending jet of a powerful cumulus cloud the number of particles probably exceeds 1 — 2 thousand per 1 cm^3. At the same time, the space charge too may constitute in thin-droplet part of the cloud near $5 \cdot 10^4$ elementary charges in $1\,cm^3$. At the same time, in a volume of 10 km^3, which is characteristic for a thundercloud, there can be a space charge to 80 k.

In the upper part of such cloud, in the region of "fused" summit, when conditions prevail for the evaporation of a certain part of droplets under the action of compensating currents [12], a comparatively small positive charge may be forming. Because of small vertical power and water content of such a cloud, it still does not manifest clear thunderstorm activity, but the electric fields may attain in it increased values.

First Stage of a Thunderstorm (stage of summer lightnings Fig. 2a). - In this stage the cloud develops to a great height. The ascending currents in its lower half become still more intense (because of liberation of the latent condensation heat). The above-considered process of charge formation will continue. Because of great vertical dimensions and great water content, the negative charge on the droplets forming and growing at condensation in the lower half or two-thirds of

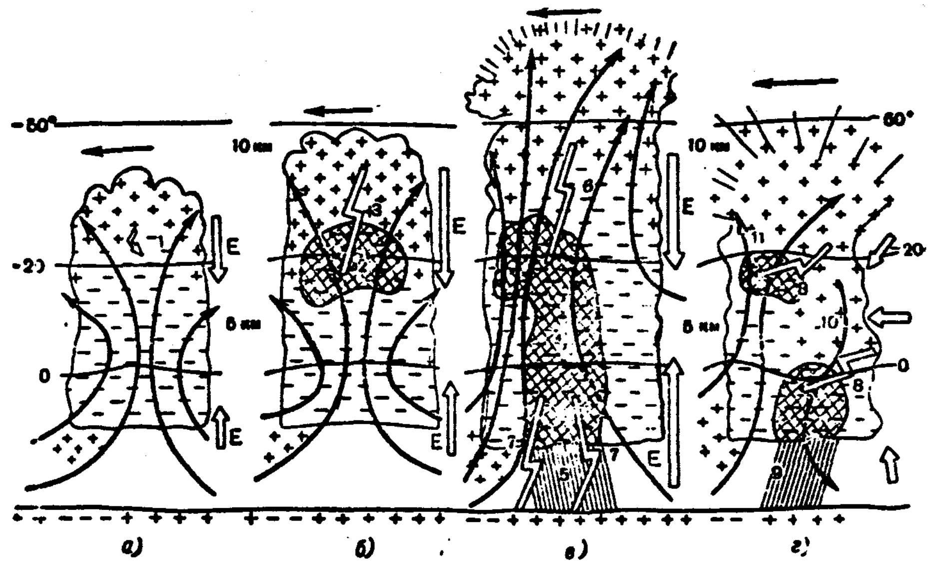

Fig. 2. - Development of a Thunderstorm

a — first stage (stage of summer lightnings; б - stage of upper discharges (stage of observable radar shadow); в — stage of maximum intensity of discharges to earth (stage of thundershowers); г — stage of storm attenuation.
1 — summer lightning; 2 — suspended cluster of coarse particles in the ascending current (updraft), carrying a great negative charge; 3 — lightning between the negative charge of coarse particle accumulation and the positive charge of the upper part of the cloud; 4 — region of coarse particles'fall; 5 — region of the thundery rain; 6 — region of upper discharges; 7 — region of intense negative discharges to ground; 8 — region of horizontal discharges in the cloud.- 9 - region of a showery rain; 10 — region of positive charges in downward currents of the collapsing part of the cloud; 11 — accumulation of coarse particles in the preserved jet of an ascending current. The magnitude and the direction of the arrows beyond clouds conditionally designate the magnitude and the direction of the vector of electric field intensity.

the cloud, will increase. In the upper part of the cloud, having reached great heights, the updraft velocity is comparatively small. Droplets reaching here from below are either in the stationary state or in the state of slow evaporation. The ions' selective sorption process leads then mostly to preferential ion OH^- yield and the droplets, alongside with the whole upper part of the cloud acquire a substantial positive charge. The electric fields may attain very high values in the upper part of the cloud. Here very mild (quiet) discharges, or discharges in the form of lightnings noted by Atlas may begin to take place [31]. We noted on the basis of prolonged visual observations, that high and powerful cumulus clouds are often attended in nighttime by summer-type lightning without sound effect and with no precipitations. In daylight these go unnoticed, but they create radiointerferences.

Stage of Upper Discharges (corresponding to that of the observable radar shadow, fig. 2б). The formation of coarse precipitation particles suspended in the cloud and inducing the appearance of a radar spot, may apparently set in at formation of the "anvil", i. e. the appearance of the crystalline icy phase in the upper part of the cloud, or without summit icing of the cumulus-nimbus cloud. The author managed to effect a few flights on free aerostats during powerful cumulus cloudiness. In one such flight the aerostat was carried by an updraft under a powerful cumulus, from which there was no precipitation. Inspite of pilo's efforts to release gas, the aerostat reached 4 — 5 km heights and was ejected through the powerful cumulus cloud's summit. During flight in the upper half of the cloud, strong turbulent motions could be observed. Wind gusts threw now and then solid ice precipitations of "sleet" (amorphous grain) type, and noise of its hitting the aerostat could be perfectly heard from the nacelle. Yet, when the aerostat passed the cloud summit, no indications of any icing were noted.

The precipitations falling from the supercooled strato-cumulus clouds in the form of rain or snow also begin often inside clouds, whose lower boundary provides no indications of crystalline structure [1].

Moore, Vonnegut and Botka [32] point out, that the most intense bright spot of radar reflection occurs about 20 minutes before the cloud summit acquires that characteristic filament shape of the icy phase.

The comparatively small precipitation particles, falling from the cloud, are found to be somehow suspended in the updraft at 4 – 6 km height, where their fall velocity becomes equal to that of the ascending current (updraft). The latter carries into that region from down below newer and newer masses of supercooled cloud drops, carrying negative charges that emerge in the violent condensation zone.

This mass of tiny supercooled and negatively-charged drops settles in the suspended accumulation of coarse particles, which then grows rapidly. Bibilashvili et al [14] point out, that the water content of such a part of the cloud reaches colossal values, up to 20 g/m^3.

List [33] studied the growth of hail when blown over by air containing supercooled droplets and crystals. He showed, that hailstones grow mainly at the expense of drop sticking. As a side result of his experiment, there was the revelation of the fact, that the electric potential of hail reached then discharge voltages.

Schaefer [34] conducted experiments in creating oily and watery mist with the help of a nozzle. He noted that during formation of coarse drops, flying through a cloud of tiny droplets, there occurs a disturbance of the electric field, often leading to an explosion probably ascribable to electric discharges from coarse drops.

Shishkin showed theoretically [1], that the growth of raindrops during their merging at fall must be attended by a rise of drops' potential. He assumes that field intensities, sufficient to start discharges, can be be induced that way.

The electric potential u_R of the coarse particles suspended in the cloud, whose radius is R, and which are formed by settling over them of supercooled cloud droplets of radius r, having a potential u_r, can be described by the formula

$$u_R = u_r \left(\frac{R}{r}\right)^2 \qquad (6)$$

which is easy to obtain in the assumption, that the space charge of the tiny drops, from whose combination the coarse particles grew, is preserved.

At the 5 mv electrokinetic potential on tiny cloud droplets, with a 3 radius of cloud droplets and 3 mm radius for the coarse ones, we find that the electric potential on coarse particles is 5 000 v. The magnitude of the charge on such a drop will be $1.6 \cdot 10^{-9}$ k.

At cloud water content of 10 g/m^3 in the zone of radar spot visibility, we obtain 80 such droplets per m^3 of air, and in each cubic kilometer there will be $8 \cdot 10^{10}$ such droplets. The space charge, concentrated in such accumulation of coarse drops is found to be equal to 120 k per 1 km^3.

We apparently obtained overrated values of space charges in a thundercloud. Charge values of several hundreds of coulombs are seldom encountered in thunderclouds. Nevertheless, the computations characterize the intensity of the phenomenon. The overrated values of the volume density of charges were obtained because formula (6) does not take into account the charge outflow from the coarse drops. Meantime, this outflow becomes more substantial as their potential rises. At field intensity of 500 v, it is close to glow discharge and appearance of streamers. Assuming the velocity of the ascending current at the center of the jet in the lower part of the cloud to be 10 m/sec, the air being saturated by moisture at 15° C temperature, we shall obtain that 3.4 g/m^3 will be condensed at every minute. Let us admit that the radius of drops is equal to 10 mk The number of such droplets, forming in 1 cm^3 per minute will be 800. Assuming, that because of selective sorption of ions OH^-, there emerges on each of them a charge characterized by an electrokinetic potential near 5 mv, which corresponds to 170 elementary charges, we shall obtain a generation near 4 k per minute in every cubic kilometer within the lower part of the cloud. As already mentioned, part of this charge settles over the coarse particle accumulation in the middle part of the cloud, while the other part is carried to its upper part. Here the particles lose the negative ions OH^- on account of equilibrium state or slow evaporation conditions and acquire a positive potential and charge relative to air.

This loss of negative charge can be estimated at $\sim 1 - 2\,k/km^3$ min. The positive electricity of the upper part of the cloud is generated with about the same intensity. Data by M. and R. Reiter [22], having shown that the pH of thunderclouds constitutes 6.37 as an average, while pH of other forms of precipitations does not exceed 5.73 – 6.14, serve as an indirect indicator that the negative charge of a thundercloud is generated as a consequence of selective adsorption of ions OH at violent condensation. And this happens at the time, when an increased acidity can be anticipated in the thundershower because of the appearance in the air of nitrogen oxides, consequence of lightning discharges. The thunderstorm phenomena at this stage are already intensely manifest. Strong thunderstorm fields are observed in the upper half of the cloud with lightning discharges between the upper positive and lower negative charges. There are cases of thunderstorms, described in literature, when these phenomena occur prior to precipitations and appearance of summit contour i.e. prior to passage of elements constituting the upper part of the cloud to crystalline state [35]. During such a stage scarce lightnings to ground may begin to take place, though still seldom. The second stage of the thunderstorm differs little from the first. The fact of the matter is that concentrations of large drop elements begin to form already prior to passage of cloud summit elements to crystalline state; these cores form along the axis of ascending currents; meanwhile, ice particles appear in the supercooled part of the cloud. From the investigations by Chestnaya and Zaytsev [16], it may be seen that the formation process of coarsened elements and of the core with increased water content is already apparent in cumulus clouds of comparatively lesser thickness. Thus, all evolves around the quantitative aspect of the matter. The accumulation of charges and the electric fields generated by them reach a level sufficient to promote an active manifestation of thunderstorm electricity precisely during the above-described second stage of development of a powerful cumulo-nimbus cloud. This coincides with the penetration of cloud summit to great heights, with partial and total formation of the anvil, and mainly with the formation of the core of suspended, radar-detectable particles.

Stage of Maximum Discharge Intensity (Fig. 26). The distinctive side of the third stage of a thunderstorm resides in the fact, that precipitation particles, having grown to large sizes, begin to fall to ground with a velocity, exceeding that of the updraft. This avalanche-like fall of the accumulation of coarse particles, charged to a high negative potential and carrying the accumulated charge of several tens or hundreds of coulombs, leads to a sharp electric field increase in the space cloud-ground. The high potential of drops favors the beginning of ionization and the appearance of lightning , starting with intense and frequent strokes to ground. At the same time the cloud is found to be a negative electrode, the ground being positive. The large drops or ice particles, falling from the upper layers and carrying negative charges, feed these negative discharges to ground.

Assuming the radius of a coarse particle being 3 mm, and its potential limited to 5 mv, each drop will carry a charge equal to $1.75 \cdot 10^{-9}$ k. Let the intensity of the thundery rain be 10 mm for 30 min. Calculation shows that 2500 drops of above-dimensions should then fall on a square meter. The total charge, contributed by these drops from above to cloud base, will be 3.4 m/km^2 min. This is entirely sufficient for feeding discharges of 2 — 7 k intensity with a frequency of one lightning flash in 2 minutes per square kilometer.

Thus, the proposed theory and scheme of thunderstorm development provide the possibility of establishing quantitatively the intensity of thunderstorm events. At the same time it becomes clear, how the value of vertical motions in the cloud can facilitate the development of thunderstorm phenomena. The value of the gravitational factor of heavy shower precipitation is also ascertained. Tverskoy [17] was first to clearly draw attention to the necessity of bringing forth both these factors in order to explain the thunderstorm phenomena. It would seem, however, that here we would be facing contradiction with the generally well known fact, that thunderstorm precipitations bear more often positive charges and the ordinary showers negative ones. It is also well known that the value of drop potential does not attain the described magnitudes. This apparent contradiction may be explained by the fact, that during ordinary heavy rains without thunderstorm activity, the negative charges having accumulated on drops, are partially preserved prior to their fall on ground. As to thunderstorm precipitations, they may either lose their charge during lightning strokes, or undergo recharging.

The cloud base is often situated at an altitude of 1500 – 2000 m. As the precipitations overcome the space separating the cloud base from the ground, they partially evaoprate. At the same time, their droplet charges are also being lost to a significant measure. This takes place as a consequence of increased desorption of ions at evaporation, as well as on account of current conductance, the latter being substantial in the space free from clouds.

In the pattern of charge distribution adopted by Simpson and his associate, the presence is noted of a small region with positive charge in the lower part of the storm. According to Williams data [30], this seat is located mainly ahead of the zone of thunderstorm precipitations. The cause of formation of that lower seat of positive charge may be in the inflow of air to the leading edge of the storm in the lower kilometer atmosphere layer from regions unperturbed by the thunderstorm. As was shown in [2], the air contains under "normal conditions" a positive space charge of atmospheric aerosol; at its convergence, a small core of positive charges can be formed under the thunderstorm. This is also helped by forces of electrostatic induction, caused by a substantial negative charge of the basic part of the thundercloud.

Attenuation Stage of a Thunderstorm (Fig. 2 v)

The onset of this stage of a thunderstorm takes place when the ascending currents, feeding the thunderclouds, decrease or attenuate. As was shown by Fedorova [18], who utilized the data of radar observations, thunderstorms attenuate when they emerge in daytime either in a valley or a low plain, or also in a maritime bay etc., and in nighttime, when unfavorable conditions occur for them above seacoast elevations and also in a series of other cases when, due to local circulation, there occur descending compensation currents.

The development of the thunderstorm itself leads at a specific stage of its expansion to the emergence in the cloud of descending currents conditioned by the hydrodynamic effect of the falling shower. As the rainfall from the thundercloud progresses, carrying with it the main part of its negative charge, and as there develop in the cloud, besides seats of ascending currents, those of descending ones, the pattern of charge distribution becomes more and more mixed. In some seats the negative charge is preserved, in others it becomes positive as a consequence of discharges, rainfall and descending motions. Accordingly, the ligthning discharges during the attenuation stage of a thunderstorm take place mainly inside the cloud. We already noted that the transition from the state of violent condesation to that of equilibrium or evaporation induces the vanishing of the negative charge and the appearance of a positive one.

CONCLUSION

The above-expounded theory of a thunderstorm allows to compute the intensity of charge generation in a thundercloud, to explain their spatial distribution and the character of lightning discharges at various stages of the storm.

The multilateral data on thunderclouds, accumulated during the latest years, and the established regularities of aerosol particle charging by way of selective adsorption of ions H^+ and OH^- as a function of aerosols' pH and of condensation or evaporation processes, can now serve as a basis for the explanation of the generation mechanism of thunderstorm electricity. The violent condensation in powerful updrafts of a thundercloud leads to the generation in its lower half of a negative space charge at the expense of the preferential adsorption of ions OH^- on the surface of cloud drops. In the upper half of the cloud, that is in the zone of stabilization and drop evaporation together with crystals, formation of a positive charge takes place at the expense of preferential yield of ions OH^- from the surface of cloud particles. The energy for aerosol particle charging originates from adsorption and condensation heat. The formation of a core of suspended particles in the ascending current jet of air containing supercooled drops or hailstones leads to substantial accumulation and localization of the negative charge. The rapid fall of the thundery rainfall from that region leads to field intensity increase between the cloud and the ground and is attended by intense negative discharges from the cloud to ground during the principal phase of the storm.

The power of thunderstorm electricity generation is found to be so much the more substantial, that the ascending currents are more intense and the height of their spread is greater; it is also a function of humidity and water content of the cloud.

***** THE END *****

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