A GUIDE TO THE STARS

by Patrick Moore

A GUIDE TO THE MOON

A GUIDE TO THE PLANETS

A GUIDE TO THE STARS

THE STORY OF MAN AND THE STARS

A GUIDE TO THE STARS

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Contents

Foreword

There can be few people nowadays who do not know at least something about astronomy. The space-rockets fired at intervals since 1957 have had their effects upon the surge of interest, but are by no means the only cause. The whole outlook of that mythical creature 'the average man' has changed during the past couple of decades, probably because science has become more a part of his everyday life. Some branches of it, indeed, threaten his very existence, and the essential thing now is for him to choose leaders who will use the new discoveries for construction instead of insane destruction.

Popular attention is focused mainly on the Moon and planets, our first space targets. This is understandable, particularly in view of the amazing developments of the past few years; not long ago the idea of landing a rocket on the Moon, for instance, would have seemed fantastic. Yet the stars, which are vastly more important in the universe as a whole, are often neglected; of course there are many excellent works available, but for every book dealing with the stars there must be at least a dozen which concentrate on the Solar System. Here, I have attempted to give a concise outline of the fundamentals of stellar astronomy. Whether I have succeeded or failed must be left to the reader to judge.

In early 1959 I remember that a British University professor of astronomy wrote a review in which all popular books came under heavy censure. His grounds were that they were scientific journalism; that they could not hope to present a full picture, and were thus bound to be misleading; and that they gave a wrong idea of what astronomy is all about. It seems to me that such an attitude is, to say the least of it, short-sighted. To expect a beginner to pick up a highly technical treatise and appreciate it at once is rather like expecting a newcomer to the piano to sit down and play a Chopin impromptu without first practising simple pieces. The rôle of a popular book is, in part, to excite interest so that those who feel drawn to the subject may follow it up.

In any case, it is surely selfish to deprive the non-scientific layman of the joy which can be drawn from the skies above him. If he knows what a star is, and has some idea of why it shines, he will gain personal satisfaction—even if he has no ambition to master the complex reasoning of mathematical astrophysics. It is for readers of this sort that I have tried to write. These pages contain no new theories or world-shaking pronouncements, and will be of absolutely no interest to well-informed readers; they are not intended to be so.

My sincere thanks are due to Dr. Gilbert Fielder, of the University of Manchester, for reading my typescript and making valuable comments. I am also most grateful to the publishers for their unfailing help and co-operation. I would like to add a note of acknowledgement to Mr. W. H. Bromage for his careful and accurate preparation of the line drawings.

PATRICK MOORE

July 27, 1959

1

The Suns of Space

Few sights are as beautiful as that of a starlit sky. On a clear night, when darkness has fallen, the whole celestial vault seems ablaze; there are hundreds upon hundreds of twinkling points, making up the constellation-patterns which the ancients named after gods, heroes and Earth-creatures.

Yet it is true to say that popular interest in astronomy is centred mainly upon the Moon and planets, which are our nearest neighbours in space. The stars, which are suns in their own right, are regarded as so remote that they are of little direct concern to us, and books written for the benefit of amateur observers tend to dismiss them relatively briefly. Remote they certainly are; but they have a fascination of their own, and during the last hundred years the message of starlight has at long last been interpreted. We know what the stars are, how they behave, and how they develop; we can study giant stars, dwarf stars, twin stars, and external systems so far away that they appear only as dim, misty patches in our largest telescopes. We also know that the Solar System in which we live represents only a very tiny part of the universe as a whole.

The Solar System is made up of one star (the Sun), nine planets, and various bodies of lesser importance such as the satellites, which are secondary worlds attending some of the planets. The Earth's only natural satellite, the Moon, is a mere 239,000 miles away from us, and so appears as a splendid object in our skies; but actually it has no light of its own, and shines only because it reflects the rays of the Sun. This is also true of the planets, and the result is that we are given a false sense of their importance. Venus, Mars, and Jupiter may at times shine far more conspicuously than any star, and it is natural for us to regard them as major members of the heavens. Yet if we look carefully at the status of the Sun, we will soon see how wrong we are.

Most people know that the Sun is a star, but how does it compare with the other stars which we can see on any dark, clear night? For instance there is Polaris, the Pole Star, which indicates the northern point of the sky, and is reasonably prominent even though it is not outstanding. Now suppose that the Sun has been taken and put at a distance from us equal to that of Polaris. Instead of a blazing disk, we will find that we cannot see it at all. If we want to glimpse it, we must use a powerful telescope—and even then it will appear only as a tiny dot of light.

Polaris, then, is much brighter than the Sun. Other stars are more luminous still, and this alone is sufficient to make our sense of importance dwindle rapidly. The Sun is large enough to hold over a million bodies the size of the Earth; if the Sun itself is simply ordinary, our tiny world fades into complete insignificance.

A brief consideration of distances will complete our humiliation. The mean distance between the Earth and the Sun, known scientifically as the astronomical unit, is 93 million miles. Of the nine planets which move round the Sun, the Earth comes third in order of distance; Mercury and Venus are closer in, the remainder farther out, with Pluto, the most remote, at an average distance from the Sun of 3666 million miles. Yet the nearest of the 'night' stars is roughly 25 *million million* miles away from us, so that on the scale of the universe even Pluto seems to be a near neighbour.

Vast stretches of this kind are very hard to appreciate, and a scale model may prove helpful, so let us begin by supposing that the distance between the Earth and Sun has been reduced to 1 foot. (On this scale the Sun will be a microscopic dot, while the Earth will be almost unbelievably tiny.) Pluto will then lie 40 feet away, and beyond there will be an immense gulf, since the nearest star will have to be placed at a distance of 50 miles. If we set our Earth-Sun model upon Westminster Bridge, the nearest star—appropriately known as Proxima—will lie somewhere in the outskirts of Cambridge.

We can extend the model further. Sirius, which shines as the brightest star in the sky, will be roughly 100 miles away, so that we will have to take it to Birmingham. Altair in the constellation of the Eagle will be as far away as London is from Plymouth. But still we are being parochial; turning to Rigel in Orion, we find that on our scale the distance will be over 6000 miles, so that to continue the model we must take a trip to Canada or South America.

Though Rigel is so remote, it shines as the seventh brightest star in the sky, so that it is hardly surprising to find that it is as luminous as 18,000 Suns put together. For the moment, however, we are concerned only with distances. We have seen that in our model Sirius is 100 miles away, Rigel 6000 miles, and so on; what then about Russia's famous moon-rocket Lunik I? We calculate that when last traced, it had travelled a distance represented on our scale by about one thirty-second of an inch. Therefore we can hardly claim that we have penetrated far into space, and perhaps we will never do so.

On the true scale, the mile is clearly inadequate as a unit of length. Astronomers would have to deal with very large numbers, and this would be an unnecessary complication. (For instance, I can correctly say that the distance between my front gate and the main road is about 7200 inches, but it is much more convenient to express it as 200 yards.) Fortunately there is an excellent natural unit available, based on the speed of light.

Light does not travel instantaneously. Careful measurements have shown that it has a velocity of 186,000 miles per second, and so in one year it covers 5,880,000,000,000 miles—nearly 6 million million.* This distance, then, is the 'light-year'; Proxima is 4·3 light-years away, Sirius 8·6 and Rigel over 500, while we know of objects whose light takes many millions of years to reach us. On the other hand light needs only 1¼ seconds to leap from the Earth to the Moon, while even Pluto, at the frontier of the Sun's kingdom, is a mere 5½ 'light-hours' off.

All these facts and figures stress that the Earth, the Sun and indeed the whole Solar System are utterly trivial on the cosmic scale. Most non-technical books give a chapter to each planet, and Mars and the Moon together are allotted as many pages as the whole universe of stars. This gives a hopelessly distorted picture, even though as a lunar and planetary observer myself I can well understand the temptation. In the present book my aim is to give a

* Scientifically it is wise to avoid the term 'billion', because the English billion (= 1 million million) is not the same as the American (= 1 thousand million), and confusion is bound to result.

brief and, I hope, lucid account of the stars, so that those who want to delve more deeply into the subject will have some idea of what to expect.

No telescope yet built will show a star as a definite disk. When we look at a planet, we can see actual surface features; Mars has its polar caps, Jupiter its belts and spots, and so on. It is quite otherwise with a star, which appears only as a point of light. Only in the case of the Sun can we obtain a detailed view, and for this reason we have to combine our telescopes with other, more complex, instruments built upon a different pattern.

The stars are not all alike. Even with the unaided eye we can see that they differ in colour; some are reddish, others yellow, and yet others pure white, which is a sure indication of differences in surface temperature—it does not need much scientific knowledge to see that a white star such as Rigel must be hotter than a yellow one such as the Sun. There is a tremendous range in luminosity, and if we represent the Sun by a candle its companions in the stellar system may be either powerful searchlights or feeble glow-worms. Some of the stars change in brightness, regularly or irregularly, and are classed as 'variables'; we also meet with twin stars, triple stars and family parties of stars, while now and then we see a real stellar explosion, when a formerly very faint star suffers a violent upheaval and turns into a 'nova', becoming very luminous for a short period before fading back into obscurity.

All these problems are linked with the all-important problem of stellar energy. To put it more graphically: What makes a star shine? It would be wrong to suppose that we are looking at burning material on the lines of a coal fire, and the true answer is much more complex, as astronomers have managed to find out. It is quite remarkable that even though we can never see a star's actual disk, we have formed a very good idea of conditions both at its surface and near its centre. During the last two decades we have delved deeply into the question of 'star-power', and in addition we have learned something about how a star is born, reaches maturity, and then sinks into old age.

Our own star-system or Galaxy contains roughly 100,000 million suns, but there are other features as well. For example, we meet with clouds of dust and gas known as nebulæ, which may be either bright or dark; shining nebulæ are illuminated or excited by neighbouring stars, while their dark counterparts show up merely because they hide objects beyond. At the fringe of the Galaxy lie the globular clusters, made up of thousands of stars arranged in the form of vast spheres, and apparently so closely packed near their centres that the starlight merges into a confused blur.

So much for our Galaxy; but even now we find that we are only at the beginning of things, since far away in space we can see other galaxies—more than a thousand million of them, so remote that in some cases their light now entering our telescopes started on its journey before the first primitive, single-celled creatures appeared in the warm seas of the young Earth. These galaxies too have their own star populations, as well as clusters, nebulæ and all the features with which we are familiar.

There is plenty of variety in the heavens, and there is always something new to see. Before discussing modern work, however, let us spend a little time exploring the past, and seeing what our ancestors thought about it all. This will be well worth doing, because astronomy has so long a tradition; it can claim, with ample justification, that it is the oldest science of all.

2

Watchers of the Stars

Men of ancient times had no idea of what the stars might be, and were indeed still completely in the dark as to the nature of the Earth.* However, they could at least observe the stars and other bodies in the sky, and many of their results were accurate, even though their interpretations were wrong. The length of the year is a good example. They fixed it as 365 days, and to them it did not much matter whether the Sun went round the Earth or the Earth went round the Sun; the period was 365 days in either case.

Peoples in China, Egypt, and Asia Minor studied the positions of the stars, and formed them into groups or constellations based upon the celestial patterns. They knew quite well that the stars appear to move across the sky 'all together', just as specks of mud upon a football will do if the football is spun round, so that the basic patterns do not alter. At a fairly early stage it was found that this does not apply to the planets, or to the Sun and Moon, which appear to wander around. Presumably, then, the Sun, Moon, and planets must be relatively near at hand.

Yet the daily motion of the star-sphere had to be accounted for, and it was generally believed that the heavens revolved round the Earth, completing one revolution each day. The Egyptians of several thousand years B.C. seem to have made some serious measurements, and they found that everything in the sky appeared to move round one particular point close to a star which is known

* Some of the old teachings seem rather peculiar in the light of modern knowledge. At one period the Hindus maintained that the flat Earth was supported by four elephants, and that the elephants stood upon a tortoise, which was in turn held up by a vast serpent swimming in a limitless ocean. On this arrangement the tortoise would seem to have the worst of matters, and it is hard to see how it could avoid being turned into something like turtle soup. However, this did not worry the Hindus, who did not understand gravity either!

to us as Thuban, in the Dragon. This point, then, had to be regarded as the north celestial pole.

The true explanation is that the Earth is a globe spinning on its axis. The axis points 'northward' to the celestial pole, and the daily apparent rotation of the heavens is due to a real rotation of the Earth. The Egyptians put a totally different interpretation on matters, but at least they knew just where the north celestial pole lay, and when they erected their famous Great Pyramid—which

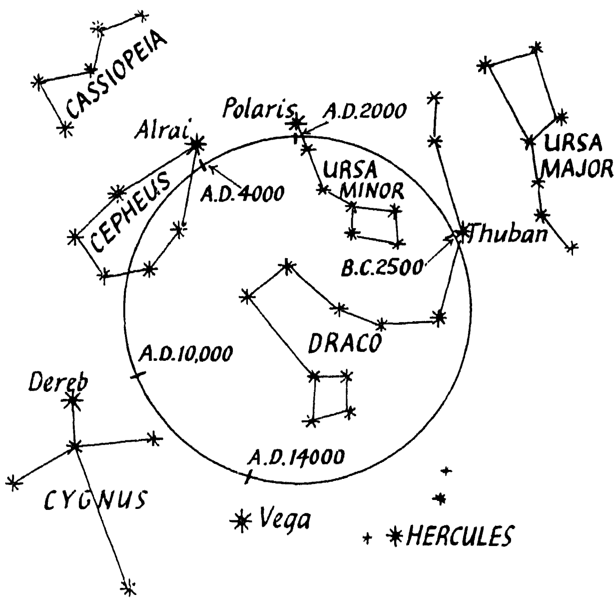


FIG. 1. The apparent movement of the North Celestial Pole. In Egyptian times the position was close to Thuban in Draco; at present it is close to Polaris, and by A.D. 14,000 it will be fairly near the brilliant Vega. The South Celestial Pole describes a similar circle; at present the polar point does not lie close to any conspicuous star.

still stands—they lined up the main gallery inside the structure according to the position of the celestial pole. This was fortunate for future Egyptologists, and it has given modern investigators a first-class clue to the date when the Pyramid was built, for oddly enough the north celestial pole is no longer where it used to be. The present pole star is not Thuban, but Polaris in the neighbouring constellation of the Little Bear.

The reason is simple enough—in principle. The Earth is not a perfect sphere; the diameter measured through the equator is 7927 miles, but only 7900 miles if measured through the poles, so that the equatorial zone bulges slightly. The Sun and Moon act upon this bulge, and so the direction of the Earth's axis shifts slowly, rather in the manner of a top which is about to fall. There are many complications to be taken into account, but the main result is that the celestial pole describes a circle in the sky, taking 25,800 years to complete the full turn. In the time of the Pyramid-builders, the polar point lay near Thuban; today it is close to Polaris, and is moving still closer. Polaris will be at its nearest to the actual pole in the year 2102. By A.D. 4000 Alrai in the constellation Cepheus will occupy the position of honour, while by A.D. 14,000 we will have a really brilliant pole star—Vega, in the Lyre.

In one way at least the Egyptians made use of their knowledge of how the heavens seem to move. Their whole economy was founded upon the annual flooding of the Nile, and obviously they wanted to know just when to expect it. They found that it started at about the date when Sirius, the brightest star in the sky, first became visible in the dawn sky, so that they took this 'heliacal rising' of Sirius to mark the beginning of the year. Even in those far-off times celestial studies were helpful from the practical point of view.

Otherwise, the Egyptians never made much progress astronomically. They were content to watch, and were reluctant to reason out just why things happen as they do. Neither must we imagine that they were the only observers of their time, and it is misleading to give them too much credit, since men in China and elsewhere were just as interested in the events taking place above them. But real advances were made only when the Greeks came upon the scene.

The story of Greek astronomy has been told many times. It began about 600 B.C. with Thales of Miletus, first of the great Ionian philosophers;* it ended in the second century A.D. with

* He was also the original absent-minded astronomer. If legend is to be believed, he was once walking along, busy looking up at the stars, when he fell into a well. I am no Thales, but I once had a similar experience involving a ditch filled with liquid mud.

Ptolemy, who was a native of Alexandria, but who belonged to the Greek school of thought.

Early ideas were just as strange as those of the Egyptians, from whom, indeed, the Greeks may have learned much of their fundamental astronomy. Anaximander of Miletus, a younger contemporary of Thales, regarded the stars as 'compressed portions of air, in the shape of wheels filled with fire, emitting flames at some point from small openings'; Xenophanes of Colophon (*circa* 500 B.C.) held that 'the stars are made of clouds set on fire; extinguished every day, they are rekindled at night like coals; their risings and settings are lightings and extinguishings respectively'. At about the same time, Heraclitus of Ephesus maintained that the diameter of the Sun was about twelve inches.

All this was far-fetched enough, but one point emerged clearly: the stars were 'fiery' and therefore hot, while the Moon was nothing of the kind. It followed that the stars were of the same nature as the Sun, and long before astronomers admitted that the Earth is nothing more than an ordinary planet it was generally agreed that the stars are suns in their own right.

About 150 years before Christ there flourished a mathematician named Hipparchus. We know practically nothing about his life, and neither have we any first-hand knowledge of his writings, all of which have been lost; but we do know that he spent many years in drawing up a star catalogue. Considering that he had to develop and build his own observing instruments, his accuracy was quite amazing. It was Hipparchus, for instance, who discovered that the polar point of the sky wanders about instead of staying still.

Later, in the second century A.D., Ptolemy of Alexandria reobserved the stars in Hipparchus' catalogue. Using the work of his great predecessor as a basis, he produced a book which is in the nature of a complete survey of astronomical knowledge up to that time. It is known as the Almagest—an Arab name, since the book has come down to us via its Arab translation—and it is of immense value. Admittedly Ptolemy made some bad mistakes, and in particular he still believed the Earth to lie in the centre of the universe, with the stars fixed to a crystal sphere. On the other hand he also made some remarkably shrewd deductions.

In the Almagest we find a list of 48 constellations. Probably these were ancient even in Ptolemy's day, but just when they were drawn up we do not know.

The stars seem to form distinctive patterns in the sky. Nearly everyone must know the seven stars of the Plough and the characteristic shape of Orion, while Australians and New Zealanders are equally familiar with the Southern Cross. Of course, the brightest stars are given special names; Sirius, so important to the Egyptians, must have been an early example. It was equally natural to form definite constellations and to give them names of their own, but we have to confess that few of the patterns bear any resemblance to the features which they are supposed to represent. It takes more than permissible imagination to make a bear out of the Great Bear, a hunter out of Orion or a winged horse out of Pegasus, while even the famed Southern Cross is much more like a distorted kite.

One nineteenth-century astronomer commented that the constellations had evidently been designed to cause as much confusion and inconvenience as possible, but this is rather unkind, since the old names are at least romantic. Moreover all the great tales are there, and the constellation names will be very familiar to readers of Charles Kingsley or Nathaniel Hawthorne. We remember how Queen Cassiopeia boasted of the beauty of her daughter Andromeda, so that the sea-god Neptune sent a monster to ravage her country; how the king, Cepheus, was forced to offer Andromeda as a sacrifice, and how the princess was rescued by the hero Perseus, who had been upon a gorgon-slaying expedition and was homeward bound upon his flying horse, Pegasus. Cassiopeia, Cepheus, Andromeda, Perseus, and Pegasus are all remembered in the sky, and we even see the snaky head of the Gorgon, Medusa, while the monster (Cetus) sprawls down to the southern horizon. The ship Argo, in which Jason sailed in his quest of the Golden Fleece, is a prominent feature of the Australian sky, and there too is Jason's old tutor the Centaur, with his human face and horse's body.

The Great Bear, perhaps the best-known of all constellations, has a legend of its own. Callisto, the daughter of King Lycaon of Arcadia, was attendant to the goddess Juno, and incurred the anger of her mistress because her beauty surpassed Juno's own. To protect Callisto, Jupiter, the king of the gods, turned her into a bear. Unfortunately Arcas, who was Jupiter's son by Callisto,* met his mother when out hunting, and was about to kill her with his spear when Jupiter turned him into a bear also, and placed both animals among the stars. To carry them to the heavens he swung them up by their tails, which—rather naturally—stretched. This is why both the Great Bear (Callisto) and the Little Bear (Arcas) have tails of decidedly un-ursine length.

We still use all the 48 constellation-names listed by Ptolemy, usually in the Latin form; thus the Great Bear becomes 'Ursa Major', while the Eagle is 'Aquila', the Lion 'Leo', and so on. These names are easy to remember, and on the whole it is best to keep to Latin. A full list, with English equivalents, is given in Appendix II.

Ptolemy's list could not be entirely satisfactory, because he did all his observing from a position north of the equator, and so could not examine the whole sky. This brings us to one of the first direct proofs that the Earth is round and not flat.

Long before Ptolemy's time, the Greek philosophers had noticed that the aspect of the heavens varies according to the position of the observer. Anyone who has done much travelling will have been struck by this effect. In Britain the north celestial pole is fairly high in the sky, so that groups near it, such as the Great Bear, never set; they are 'circumpolar', and remain above the horizon all the time, so that they are always to be seen when the sky is clear and dark. Stars farther from the Pole, such as the brilliant orange Arcturus, are not circumpolar, since for a part of their 24-hour sweep round the Pole they are below the horizon.

The farther north we travel, the higher becomes the Pole Star, and an observer standing on the north pole of the Earth would see Polaris straight overhead, at the 'zenith'. In fact, the altitude of the celestial pole above the horizon is equal to the observer's latitude. If you are in London, where the latitude is 51½ degrees, Polaris will be 51½ degrees above the horizon; from Oslo (latitude 60 degrees) Polaris will be at 60 degrees, and so on. The latitude of the north pole is 90 degrees, so that from here this is also the altitude of Polaris.†

* The ancient Olympians were not noted for their strict moral code.

† For the purpose of this argument, we need not bother about the fact that Polaris is not situated exactly at the north celestial pole.

If we move toward the equator, Polaris sinks in the sky. By the time we reach the equator, our latitude is 0 degrees, and so Polaris has an altitude of 0 degrees, which means that it lies on the horizon, while from south of the equator Polaris can never be seen at all. To compensate, groups near the opposite pole have come into view, and we have the Southern Cross, Argo, Centaurus and the rest. Londoners never see these constellations, just as Australians never see the Great Bear.

The Greeks realized the significance of all this. In particular they noticed that Canopus, the second brightest star in the whole sky, rises above the horizon from Alexandria—where Ptolemy lived—but can never be seen from Athens. Such effects would be impossible to explain on the theory of a flat Earth, but are only to be expected if the Earth is a globe.

Since the groups near the south celestial pole remain permanently below the Alexandrian horizon, Ptolemy could know nothing about them. For that matter, his 48 constellations did not even cover the whole of the sky which he could see, since some areas were left out. Later astronomers extended his list, even to the extent of forming new groups by chopping pieces off the original 48, until nowadays we recognize 88 constellations. Unfortunately the old system of mythological names has not always been followed, and in the southern hemisphere we find names such as Telescopium (the Telescope), Antlia (the Airpump), and Octans (the Octant). Octans contains the south celestial pole, which is not marked by any conspicuous star.

Twelve of Ptolemy's constellations seemed particularly important, as they made up the Zodiac. This is the belt around the sky in which the Sun, Moon and planets are always to be found. The explanation is simple enough. The planets move round the Sun in roughly the same plane, so that if we draw a chart of the Solar System on a flat piece of paper we are not far wrong. Of the planets known in ancient times, only Mercury has an orbit whose plane is inclined by more than 5 degrees to that of the Earth, and therefore the planets are to be seen only in certain directions against the starry background. The 12 Zodiacal constellations form a band right round the sky, beginning with Aries (the Ram) and ending with Pisces (the Fishes).

The Zodiac was closely linked with astrology, the so-called science which is best described as 'the superstition of the heavens'. It used to be thought that the positions of the Sun, Moon, and planets affected human destiny, so that men and women born at a time when the Sun was in (say) Aries would differ in character and fortune from those born when the Sun was somewhere else in the Zodiac. Actually, astrology is pure nonsense from beginning to end, and it has nothing whatever to do with true astronomy. Luckily modern 'astrologers', like the flat-earthers, flying saucer enthusiasts and others of their kind, are more or less harmless.

Another feature of Ptolemy's catalogue was that he divided the stars into grades or 'magnitudes' of apparent brilliancy. The system was not Ptolemy's own, but wisely he adopted it. The general scheme is to class bright stars in magnitude 1, fainter stars in magnitude 2, and so on down to magnitude 6, which includes the dimmest stars visible to the naked eye under average conditions. It is important to remember that the smaller the magnitude, the brighter the star; there is some analogy with a golfer's handicap, since here too the most brilliant performers have the lowest handicaps. We can carry this analogy still further. Really outstanding golfers have handicaps which are lower than zero (scratch), and similarly the most prominent stars have zero or even negative magnitudes. Sirius, the brightest of all, is minus 1·4. After telescopes were invented, in the seventeenth century, stars fainter than the 6th magnitude could be detected, and nowadays giant instruments can take us down as low as magnitude +23.

So much for the stars in Greek astronomy. We can see that despite their catalogues and despite their studies of celestial movements, the ancients knew nothing about the stars themselves. It was suspected that a star must be fiery, but there was no proof, and without telescopes proof was impossible to obtain.

The following centuries may be dismissed in a few lines. During the so-called Dark Ages which followed the decline of Greece and the collapse of the Roman Empire, science was more or less at a standstill. When it revived, it was by way of astrology. A thousand years ago the Arabs were busy drawing up star catalogues which were more accurate than Ptolemy's, and the apparent movements of the celestial bodies were worked out with great skill. Naturally enough this was a great help to navigators, and astronomy became more and more important from the practical viewpoint—particularly to sailors.

Two more observers must be mentioned before we come to the telescopic era. During the latter part of the sixteenth century a new catalogue of naked-eye stars was drawn up by Tycho Brahe, a Danish astronomer who laboured at his task for many years. Most of his interpretations were wide of the mark, and he was convinced that the Earth must lie at the centre of the universe; he was also an enthusiastic astrologer, and to describe him as 'touchy' would be a gross under-statement. Luckily there was nothing the matter with his measurements, and the instruments which he set up at his island observatory on Hven, between Denmark and Sweden, were by far the best of their time. On his death, in 1601, he left his measurements to his assistant Johann Kepler, who used them to prove finally and decisively that the Earth goes round the Sun. This was possible because Tycho had also measured the apparent positions of the planets, and Kepler was able to work out how the planets actually move.

Yet another catalogue was produced by a Bavarian, Johann Bayer. It was published in 1603, and was notable because it made use of the modern system of star nomenclature.

Bright stars such as Sirius and Canopus have individual names, but it is clearly out of the question to name every star in the sky. Bayer therefore took each constellation and gave its stars Greek letters. Ideally the brightest star in each group was Alpha, the second Beta, and so on down to Omega, the last letter in the Greek alphabet. In this case the leader of Ursa Major would become Alpha Ursæ Majoris (Alpha of the Great Bear) and so on. As is usually the case, the scheme was not strictly followed, and we have many departures from the rule; in Ursa Major itself, for example, the brightest star is Epsilon, followed by Eta, Alpha, Zeta, Beta, and Gamma in that order. However, the basic idea was so convenient that everyone adopted Bayer's lettering. Since the Greek alphabet is always used in this connection, it may be as well to give a complete list:

α Alpha	ι Iota	ϱ Rho
β Beta	ϰ Kappa	σ Sigma
γ Gamma	λ Lambda	τ Tau
δ Delta	μ Mu	υ Upsilon
ε Epsilon	ν Nu	φ Phi
ζ Zeta	ξ Xi	χ Chi
η Eta	ο Omicron	ψ Psi
θ Theta	π Pi	ω Omega

The special names given to most bright stars were not discarded, so that brilliant objects have both individual names and Greek letters; Sirius is Alpha Canis Majoris (Alpha of the Great Dog), while Rigel is Beta Orionis (Beta of Orion) and so on. However, many of the clumsy proper names given to fainter stars have gradually dropped out of use. This may be as well, since the old names include such tongue-twisters as Zubenelchemale, Azelfafage, Alkaffaljidhina, and Dschubba!

With Tycho and Bayer, the first period of stellar astronomy came to an end. In the first decade of the seventeenth century the chance discovery of a Dutch spectacle-maker opened a new era—the era of telescopic astronomy, which has led to our finding out not only how the stars move, but also what they are.

3

The Stellar Heavens

According to some authorities, Nero, who has the doubtful distinction of being the worst emperor whom even Rome had to suffer, wore a quartz monocle. Whether this is true or false seems uncertain; certainly aids to sight such as spectacles were quite unknown in Classical times. However, spectacles had come into use by the beginning of the sixteenth century, and it seems rather curious that the principle of the telescope was not discovered until 1608.

The honour goes to Hans Lippersheim, of Middelburg in Holland. At once he achieved fame, and reports of his invention spread as quickly as any news could do in that era of slow, unreliable communication. Most people know the story of how Galileo, professor of mathematics at the University of Pisa, heard about it and built telescopes for himself; well known, too, are Galileo's discoveries of the satellites of Jupiter, the rings of Saturn, the phases of Venus and numerous other wonders hitherto utterly unknown. In the field of stellar astronomy, Galileo found that there was vast scope, and in particular he saw that the luminous band known as the Milky Way is made up of countless faint stars.

One result of all this was that better measures of star positions became possible. As soon as telescopic sights became available, the accuracy of observations could be greatly increased. Of course, the early telescopes were built upon a pattern which seems curious to us; even so, they were far better than nothing.

The telescopes built by Galileo and his contemporaries were 'refractors'; an instrument of this sort collects light by means of a lens or object-glass, the magnification being accomplished by means of a smaller lens known as an eyepiece. (The reflecting telescope, in which the light is collected by a mirror instead of an object-glass, did not come upon the scene until about 1670, when Isaac Newton developed it.) For various reasons which need not concern us at the moment, early refractors produced an unwelcome amount of false colour, so that any bright star would appear to be surrounded by rings of gaudy hues which had no real existence. One method of reducing the trouble was to make the telescopes very long, so that in some cases the object-glass had to be fixed to a mast.

Such an 'aerial telescope' was used by Johann Hevelius of Danzig, who began his active observing career in 1644. His main instrument had an object-glass fastened to a mast 90 feet high, and must have been remarkably awkward and cumbersome to use. All the same, Hevelius carried out excellent work; he made the first reasonably good map of the Moon, and also produced a catalogue of over 1500 stars.

The whole question of star cataloguing came to a head during the reign of Charles II, not because of any direct concern with pure science, but because it was of practical importance to the British nation. Britain has always been a seafaring country, and in those days the only way in which a sailor could determine his position, when far out to sea, was by means of the stars—in fact, by what we now term astro-navigation. Latitude is relatively easy to find, as we have seen, since all that needs to be done is to measure the altitude of Polaris and then make a few corrections. Unfortunately, longitude is much more troublesome, and it was therefore of more than academic interest when a Frenchman, about whose personal career we know virtually nothing, announced that he had worked out a method whereby longitude might be determined.

Nobody would claim that Charles II was an ideal king, but neither would any rational critic deny that he was a remarkably clever man. Evidently he realized that there might be some foundation for the Frenchman's claim, and he referred the whole matter to a scientific committee. He was fortunate in that he was able to call upon men of unusual talent; the Royal Society had been founded, and among the great figures of the time were scientists of the calibre of John Flamsteed, Edmond Halley, the strange, ill-tempered genius Robert Hooke, and—of course—Newton.

The Rev. John Flamsteed, who was already widely known as a careful and painstaking observer, strongly supported the idea. In brief, it involved measuring the position of the Moon relative to the stars. The Moon is so close to us that it moves relatively quickly across the sky, and we may consider the sky as a clock face, the Moon being a hand which moves across it. The position of the 'hand', i.e. the Moon, therefore gives the time. There are many complications, but if we can measure the position of the Moon really accurately we can find the time on the standard meridian of the Earth, and the longitude of the observer can be worked out.

This was all very well, but obviously it meant knowing the star positions very exactly, to say nothing of the precise way in which the Moon behaves. Tycho's star catalogue, which was already nearly a century old, was not good enough, and the only solution was to compile a better one. Charles therefore decided that the stars must be 'anew observed, examined and corrected' for the use of British seamen. This required a special establishment, and Greenwich Observatory was the result.

In view of its present status in world science, the early history of Greenwich is not without its amusing side. In typical fashion Charles raised the money for the original building by the sale of 'old and decayed' gunpowder, and commissioned Sir Christopher Wren, himself a former professor of astronomy, to undertake the design. The Observatory was completed in 1675, and Flamsteed was placed in charge of it, so becoming the first Astronomer Royal. However, the King's generosity did not extend to providing Flamsteed with telescopes or any other instruments, and the would-be star cataloguer had to fend for himself. His salary, £100 a year, was hardly princely, and altogether he worked under difficulties.

Flamsteed was a man who disliked being hurried; moreover he was a perfectionist, and he was both irritable and temperamental. His relations with two of his great contemporaries, Newton and Halley, were—to put it mildly—distant, which was an added complication. Years passed by with Flamsteed still working away and still refusing to publish his results. Then, in 1704, Prince George of Denmark, husband of the new sovereign Queen Anne, offered to pay for the publication of the catalogue, and Flamsteed handed a manuscript copy to a Royal Society committee headed by Newton. Flamsteed added, however, that the catalogue was not yet in its final form, and stipulated that it should not be printed until everything had been re-checked, though the actual observations could go forward.

For a number of reasons, including the death of Prince George in 1708, printing was held up, and still Flamsteed did not produce the final version of his actual catalogue, for which all his fellow astronomers were waiting. Finally, in 1711, the Committee published one large book containing not only Flamsteed's observations, which he had passed for publication, but also the catalogue, which he had not. To make matters worse the catalogue contained errors, and was accompanied by a preface, written by Halley, which could not be anything but harmful to Flamsteed's reputation.

A veil is best drawn over the undignified squabble which followed. None of those concerned emerge with much credit, and when Flamsteed managed to secure a large number of copies of the book he burned them publicly 'that none might remain to show the ingratitude of two of his countrymen'. He still intended to finish the proper catalogue, but died before he could do so, and it was eventually published in 1725 after being completed by two of Flamsteed's assistants, Crosthwait and Sharp.

The whole episode spread over half a century, from 1675 to 1725, but luckily the catalogue was worth waiting for, and was by far the best of its time. Judged by modern standards its accuracy is, of course, low; nowadays we have the advantage of much better instruments than those available to Flamsteed, to say nothing of photography, which has revolutionized all astronomical science. This is no reflection upon the first Astronomer Royal, for whosc work no praise can be too high.

All these early observers lived in the northern hemisphere, and so stars near the south celestial pole were perforce neglected. Edmond Halley, later to succeed Flamsteed as Astronomer Royal, determined to study them, and in 1676 he left Britain for the island of St. Helena, where he remained for long enough to catalogue 360 important southern stars. Halley, best remembered for his work upon the path of the great comet which now bears his name and which will be bright once more in 1986, was one of the most attractive scientific personalities of his time. He was 63 when he became Astronomer Royal, and showed his natural optimism at once by embarking upon a series of observations of the Moon's position which he knew would take him nearly twenty years. It is pleasant to record that he completed the main task before his death in 1642.

One of Halley's greatest contributions to stellar astronomy was his discovery that three bright stars—Sirius, Procyon, and Arcturus—had showed slight but perceptible movement in the heavens since

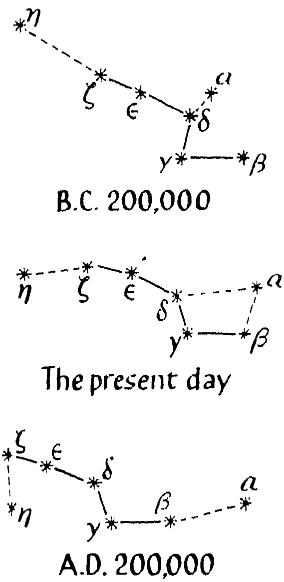


FIG. 2. The changing shape of the Plough. It will be seen that while five of the Plough stars (Zeta, Epsilon, Delta, Gamma and Beta) are moving in more or less the same direction, the remaining two (Eta and Alpha) are not.

the age of Ptolemy. This brings us to the question of 'proper motions'.

We have seen that the constellation patterns appear to remain the same for year after year, century after century. This is not because the stars are fixed in space; on the contrary, each star is moving at a tremendous rate. The reason for the apparent permanence of the constellations is that all the stars are so remote. An everyday analogy may be drawn here. If you watch a jet aircraft very high in the sky, it appears to be crawling along so slowly that you have to check carefully to see that it is moving at all; yet its real speed may be several hundreds of miles per hour. Its distance appears to 'slow it down', and the stars, which are so much more distant still, are 'slowed down' almost to a halt. It is not always easy to remember that in actual fact, the stars are moving about at speeds of many miles per second.

However, each star has a tiny individual or 'proper' motion relative to its companions, and over very long periods of time these proper motions accumulate sufficiently to become noticeable. To show what is meant, let us look at the seven Plough stars of Ursa Major, the Great Bear, in the past, present, and future.

All seven are of about the second magnitude with the exception of Delta Ursæ Majoris, or Megrez, which is decidedly fainter. The characteristic Plough-shape, shown in the middle diagram, is

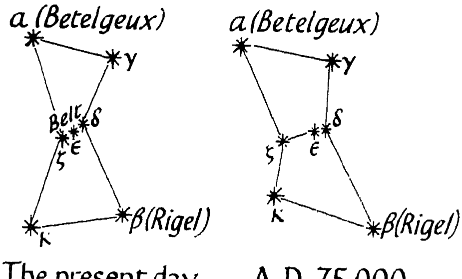


FIG. 3. The changing shape of Orion.

familiar to most people. The arrows attached to the stars indicate directions of motion; and it will be seen that while five of the stars are going much the same way, the remaining two (Dubhe and Alkaid) are not. By A.D. 200,000 the change in shape will have made our 'Plough' unrecognizable; 200,000 years ago the pattern would have been equally strange to our eyes. It is worth adding, incidentally, that something can be learned by comparing Alkaid with the first star in the Plough-handle, Alioth. The magnitude of Alioth is 1·6, and of Alkaid 1·9, so that Alioth appears slightly the brighter—but actually Alkaid is much farther away from us, and is the more luminous of the two.

All proper motions are very slight, and so far as we are concerned we may say that the constellations are 'permanent' inasmuch as they do not alter perceptibly in the course of a lifetime. The nearest stars seem in general to move the fastest, but even the greyhound of stellar skies, a faint object known as Barnard's Star, takes nearly two centuries to creep across the heavens by an amount equal to the apparent diameter of the Moon. Halley's detection of the proper motions of Sirius, Procyon, and Arcturus was therefore a major feat.

Of course, these individual proper motions have nothing to do with the apparent shift of the celestial pole as described above. The movement of the pole is due to a real shift in the direction of the Earth's axis, and has no direct connection with the stars themselves.

Ptolemy's 48 constellations did not even cover the whole of the northern sky, and the spare regions were filled in by later cataloguers. Also, the far southern groups in turn had to be divided up into constellations, a process carried out by various astronomers during the sixteenth and seventeenth centuries. There were also several attempts to revise the whole nomenclature. In 1627, for instance, Julius Schiller wanted to replace the mythological names by those of saints, popes and bishops, so that Taurus the Bull would have become 'St. Andrew', Lyra the Lyre 'the Manger', and Andromeda 'the Holy Sepulchre'. In our own time we have had to contend with the entirely barbarous suggestion of renaming the constellations on a political basis. To observe stars in Sir Winston Churchill, President Eisenhower and Mr. Krushchev might please some people, but it is hardly necessary to add that scientists have given the scheme a decidedly frigid reception!

To measure star positions, we must have a standard of reference. Much the same problems arise on Earth, where we determine position by latitude and longitude; latitude is the angular distance north or south of the equator as measured from the centre of the globe, while longitude is the angular distance east or west of the Prime Meridian, measured in the same way. The equator, of course, is in a definite position, so that latitudes may be reckoned from it, but the only reason why we use the Prime Meridian as a standard of reference is that all nations have agreed to do so.

A 'great circle' is marked by a curve which runs right round the

Earth, and whose plane passes through the Earth's centre. In other words, if you could slice the Earth through a great circle you would cut the globe exactly in half. The Prime Meridian is the great circle passing through the North Pole, the South Pole, and Greenwich Observatory. Obviously, this is no coincidence; the meridian was selected simply because Greenwich Observatory happened to be there, and was taken as longitude 0 degrees.*

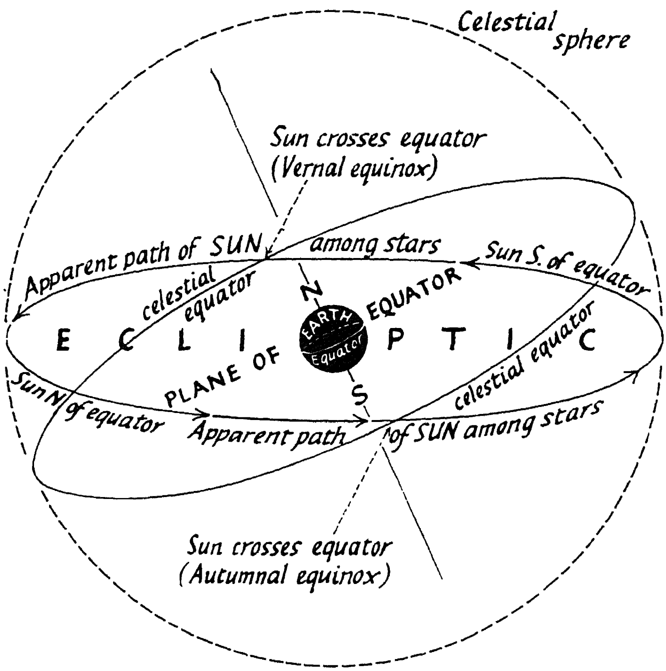


FIG. 4. Diagram of the Ecliptic and the Celestial Equator.

For the sky, we have to find an 'equator' and some equivalent of the Prime Meridian. It is convenient to imagine that the sky is solid, so that lines can be drawn on the 'celestial sphere'. If we

* For many years the French took their 0 degrees to be the longitude of Paris Observatory, which led to a great deal of confusion, but eventually there was an international conference which—unlike modern international conferences—reached agreement, so that henceforth everyone adopted the Greenwich meridian as marking 0 degrees.

project the plane of the Earth's equator on to this sphere, we naturally have the celestial equator. It is then possible to measure the angular distance of any star north or south of the equator, which gives the Declination—minus 16° 39′ in the case of Sirius, for instance, since this is the star's angular distance south of the equator. Obviously, the declination of the north celestial pole is +90°; Polaris has a declination of +89° 2′, and is thus less than a degree away. (To be precise, corrections have to be made so that the measured angles are referred to an imaginary observer who is placed at the centre of the Earth.)

For east-west reckoning we turn first to the ecliptic, which is defined by the plane of the Earth's orbit. This intersects the celestial sphere in a great circle which will be the apparent path of the Sun in its journey among the stars. The ecliptic lies at an angle to the celestial equator, since the plane of the Earth's equator is tilted at an angle of about 23½° to the plane of its orbit. About March 21 each year the Sun reaches the celestial equator, journeying from south to north; this is where the ecliptic and the equator cross, and is called the First Point of Aries or 'Vernal Equinox'. Here is the source for our prime meridian of the sky, and we take it as marking our zero point. Star positions which are measured from it in an eastward or anti-clockwise direction along the celestial equator are measures of the star's Right Ascension.

Right Ascension may be measured in degrees, but more usually in hours, minutes, and seconds of time. This may sound confusing at first, but actually it is very convenient. A star is said to culminate when it reaches its highest point above the observer's horizon, and is on his meridian; the right ascension is the time-difference between the culmination of the First Point of Aries and that of the star concerned.

An example should make this quite clear. Since the Earth spins on its axis once a day, the First Point of Aries is bound to culminate each day (often, of course, it does so during daylight, but this makes no difference to the argument). Sirius, the Dog-Star, culminates 6 hours 43 minutes after the First Point of Aries has done so, and consequently the right ascension of Sirius is 6 h. 43 m. Vega, the brilliant bluish star in the constellation Lyra, culminates 18 h. 35 m. after the First Point of Aries, and so on.

This 'First Point' is so named because it used to lie in the constellation Aries, the Ram. Oddly enough it no longer does so, but has shifted into the adjacent group of Pisces, the Fishes. This has happened because of 'precession', the movement of the celestial pole.

Remember that the celestial pole shifts slightly, because of the pull of the Moon, the Sun, and other bodies upon the equatorial bulge of the Earth. If the celestial pole moves, the celestial equator must move too, and this in turn changes the position of its intersection with the ecliptic. Gradually, then, the right ascensions of the stars change, and in any list you will see that the figures are given for some particular year. The values for Sirius and Vega quoted above are for 1950, but by now they are very slightly different. The alterations are so slow that there is no need to publish new tables every year, but corrections are necessary over several decades. Since Classical times, the effect has shifted the 'First Point' of the sky out of Aries altogether; Pisces, which used to be the last constellation of the Zodiac, has now technically become the first, although it is not generally regarded as such.

Well-mounted telescopes are equipped with setting circles, graduated according to right ascension and declination. If you know the values for any particular object, all you have to do is make some calculations, set the circles by swinging the telescope to the indicated position, and look through the eyepiece. If the adjustments are correct, and you have made no mistake in your figures, the desired object will be in the field of view. Of course the object is apparently moving across the sky, because of the Earth's rotation, and the telescope will have to be fitted with mechanism to act as a drive, swinging the whole instrument slowly and steadily to keep the object in sight.

We have digressed rather widely from our historical survey, but the whole question of star positions is so important that it cannot be glossed over lightly, since precise measurement is essential in modern stellar astronomy. For that matter the positions of the Sun, Moon, and planets can also be given on the same system, though since they wander around the sky their right ascensions and declinations alter from night to night.

Flamsteed built upon the work of men such as Tycho, and later astronomers carried on in a similar way. There is no space here to describe the various catalogues which have been produced, but now that photography has come to our aid we have reached an accuracy which would have surprised our predecessors. Meanwhile, it is time to turn to another fundamental problem—that of the distances of the stars.

4

Measuring the Universe

Flamsteed, the first Astronomer Royal, catalogued the stars. His successor, Edmond Halley, recognized proper motions, while in 1728 the man who was later to become the third holder of the office, the Rev. James Bradley, determined to attack a still greater problem—that of finding out how remote the stars really were. The method he proposed to use was that of 'parallax'.

The principle of the method is quite simple, and once again we have an everyday analogy. Suppose that a surveyor wants to measure the distance between a small marker-post, P in the diagram, and a point T on a tower on the far side of a river. If he has no means of crossing the water, he can still do all that is necessary by means of calculation.

First suppose that he measures out a base-line AB, with P in the

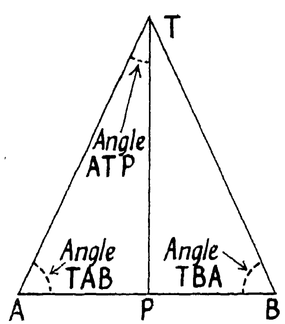


FIG. 5. Principle of parallax.

middle of it and with AB and TP at right angles to each other. Using his theodolite, he measures the angles TAB and TBA. Since the three angles of a triangle add up to 180 degrees, the third angle (ATB) of the big triangle follows at once. Now we have found out all the angles of the triangle, and in addition we know the length of the base-line AB—because we can measure it directly. By drawing or by calculation, we can now evaluate all the distances in the triangle. The line TP splits the big triangle into halves, and therefore the distance TP can be found as well. The problem is complete, and we have the distance of our tower. The angle ATP (or BTP, which is equal to it) is known as the parallax of the point T with reference to the 'base-line'.

If you want an even simpler example, hold up a finger, shut one eye, and then line up your finger with some relatively distant object such as a chimney-pot. Now, without moving your head, use your

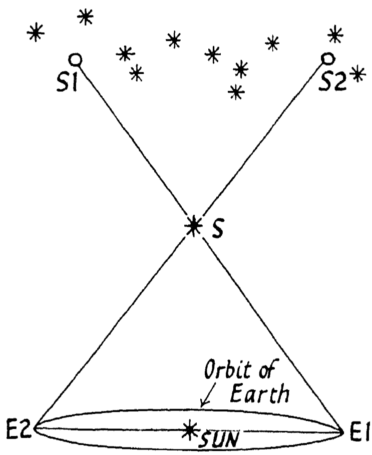


FIG. 6. Parallax of a star. S is a nearby star; the orbit of the Earth round the Sun is shown. When the Earth is at E1, the star S will appear in position S1; with the Earth at E2, the star will be at S2. The shift may be measured by reference to more distant stars. It must be stressed that for the sake of clarity, this drawing is completely out of scale; the actual parallax shifts of even the nearest stars are very small indeed. They are measurable only because of the long base-line; the distance between E1 and E2 is 186,000,000 miles.

other eye—and you will see that the lining-up of your finger with the chimney-pot is no longer exact, because you are viewing your finger from a slightly different direction. Returning to the diagram, your finger is represented by T, your nose by P and your two eyes by A and B. If you could measure the apparent shift you could obtain the parallax, and complete the calculation as before.

This is straightforward enough when the object to be measured is fairly close, but with greater distances you need a longer base-line, as otherwise the shift due to parallax will be too slight to be measured at all. Bradley knew this, and realized that the Earth, with its diameter of less than 8000 miles, would not be nearly large enough. The best solution was to make use of our yearly motion round the Sun.

The distance between the Earth and the Sun is known; it is about 93 million miles. Therefore the diameter of the Earth's path is twice 93 million miles—186 million miles, as shown in the second diagram. If S is a comparatively near star, and we can regard the background stars as being at an infinite distance, the parallax of S will become measurable. If its apparent position is S1 on any particular date, the position will have shifted to S2 six months later, when the Earth is on the other side of the Sun. We can then measure the angles just as our surveyor did, and work out the distance of the star.

This again is simple in theory, but unfortunately there are dozens of complications. To begin with, the Sun itself is not fixed in space, and this introduces an error at the outset. We must be careful to select a close star, which is not easy when you do not know the distance of any of them. Moreover, the angle of parallax is bound to be very small, and cannot amount to as much as one second of arc; when we remember that one second of arc is the apparent diameter of a penny seen from a distance of 12 miles, it is clear that Bradley had set himself a real problem, and that the diagram given here is hopelessly out of scale. Not surprisingly, Bradley failed—but he did make a discovery which was as fascinating as it was unexpected.

His target star was Gamma Draconis, which is of magnitude 2·4. Bradley selected it mainly because it passes directly overhead at Greenwich, and this meant that he could watch it regularly by means of a special telescope fixed in a vertical position; he was in effect looking straight 'up' at the star as it crossed the overhead point or zenith.

Bradley found apparent movements indeed, but they did not seem to be due to parallax. He was badly puzzled, and ordered a new telescope which allowed him to examine other stars as well. All of them showed the same tiny shifts. This in itself proved that parallax could not be the cause, and one day when Bradley was out sailing on the Thames he realized the answer. If the direction of the boat were changed slightly, the mast-head shifted, due not to a change in wind direction but to an alteration in the boat's course. Many people have unconsciously noticed something of the sort; if you go out in a shower of rain, and the drops are falling almost vertically, you will have to hold your umbrella forward if you are to avoid being drenched. Only if you stand still will you need to hold the umbrella straight above your head.

Light, as was known even in Bradley's time, does not travel instantaneously, but has a velocity of 186,000 miles per second. Therefore, the light coming from a star will always show an apparent displacement toward the direction in which the Earth is moving. Since the Earth's rate in its orbit round the Sun is some 18½ miles per second, and the direction is changing all the time simply because our orbit round the Sun is practically a circle, the stars will show regular annual shifts, returning at the end of one year to their original positions. The effect is termed 'aberration'.

Bradley's discovery of aberration made him famous, and had a great deal to do with his appointment as Astronomer Royal when Halley died in 1742, but it did not help toward a solution of the main problem. When Bradley died after twenty years in office, the distances of the stars remained as baffling as ever. By then a young Hanoverian musician had arrived in England—a musician who was to become one of the greatest astronomical observers of all time, and who in turn did his best to work out the scale of the universe.

Friedrich Wilhelm Herschel, better known to us as Sir William Herschel, began his career as a bandboy in the Hanoverian Guards. Militarism did not appeal to him at all, and when he came to England it was with the intention of earning his living as an organist and music teacher. For some years he was organist at the Octagon Chapel in Bath,* but his main interest was astronomy, and he built

* Some years ago, when I was in Bath, I decided to find the Octagon Chapel to see whether it contained any Herschel relics. I searched for some time, and finally asked a bearded veteran, who told me pityingly that the Chapel had been demolished during the reign of Queen Victoria. Until recently Herschel's later home, at Slough, was preserved just as it had been during his lifetime, but it has now been sold, and the relics dispersed. At the time when these words are written, energetic efforts are being made to save the house from demolition and keep it as a Herschel memorial.

reflectors which were the best of their time, the greatest of which had a mirror 48 inches in diameter. In 1781 he discovered a new planet, the one now known as Uranus, and he was appointed King's Astronomer—not Astronomer Royal, by the way—so that he was able to give up his musical career and spend the rest of his days working for science.

Herschel was nothing if not methodical. Helped by his sister Caroline, he set out to 'review the heavens', his main idea being to find out how the stars are distributed in space. Like Bradley, he proposed to measure distances by parallax, but his method was a variation on the main theme, as he planned to make use of the double stars.

Pairs of stars are common in the sky. Some of them are visible without a telescope; if for instance you look closely at Theta Tauri, close to the bright orange-red Aldebaran, you will see that it is made up of twins. Mizar or Zeta Ursæ Majoris, the second star in the Plough-handle, has a 5th-magnitude star (Alcor) beside it, and any small telescope will show that Mizar itself is made up of two components, one rather brighter than the other. Herschel's telescopic sky-sweeps yielded a rich harvest, and by 1785 he had published two catalogues of double stars, raising the total known number to over 700. He was ready to begin his real task.

Let us suppose that two stars, A and B in the diagram, lie in more or less the same direction in space as seen from Earth, but that B is much more remote than A. The effect will be that of a double star, as drawn in the inset. If the two components are equally luminous, B will naturally appear fainter than A, though since the stars range from 'glow-worms' to 'searchlights' it is unwise to jump to any conclusions on this score.

On Herschel's reasoning it should often happen that while B is too remote to show any measurable parallax shift, A is close enough to do so. We can thus regard B as our stationary background, and measure the yearly shift of A relative to it. When solar motion, aberration, and all the other complications have been taken into account, the distance of A should be found.

It all seemed feasible, but no shifts came to light. The brighter components of double stars obstinately refused to show parallaxes as Herschel had hoped. This was indeed curious, and Herschel started again, re-measuring many of the pairs in his catalogues. Like Bradley half a century before, he made a discovery which was entirely unexpected. In many cases the components of double stars appeared to be moving round each other, much as two bells of a dumbell will do when twisted by their joining arm. This, of course, is the way in which the Earth and Moon move together round the Sun—though here the Earth is so much more massive than the Moon that the 'balancing point', or centre of gravity of the combined system, lies within the Earth's globe.

The inference was obvious. For such stars, the components were physically associated, and lay at the same distance from us.

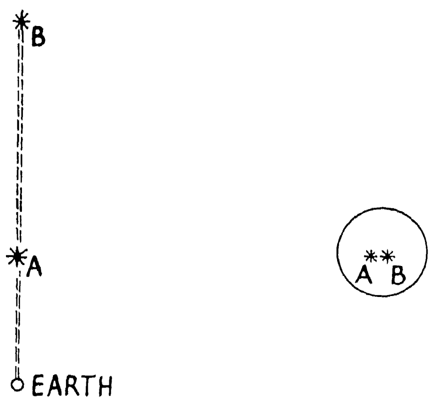


FIG. 7. An optical double star. As seen from the Earth, stars A and B lie in almost the same direction, and the telescopic appearance will be as shown in the right-hand diagram. Actually, star A has no association with star B. Optical doubles of this sort do occur, but binary systems, in which the two components are genuinely associated, are much more common.

Herschel had failed in his main object, but he had discovered true star-pairs or 'binaries'.

Of course, not all double stars are binaries. There are cases when the arrangement is very much the same as shown in the diagram, but oddly enough these false or optical doubles are the exception rather than the rule, while binary pairs are extremely common in space. Meanwhile, Herschel had to admit defeat; we know now that though his instruments were good, they were not adequate to reveal stellar parallaxes.

Herschel died in 1822. During the following fifteen years the problem of stellar distances was taken up by three more observers, all of whom obtained definite results; they were Thomas Henderson in South Africa, Friedrich Bessel in Germany, and F. G. W. Struve in Estonia, which was then (as now) included in Russia. The methods which they used were basically the same, though different in detail, and Bessel must be awarded the honour of priority—since he was the first to publish his results, though actually his measures were made some time after Henderson's.

Bessel was quick to make his mark in the astronomical world. He was appointed Director of the Observatory of Königsberg at the early age of twenty-six, and set himself to tackle problems of star-cataloguing. At that time Bradley's catalogue was the best in existence, and Bessel began to overhaul it, extending it at the same time, until at last he produced a list of the positions of 63,000 stars. Some of these stars showed proper motion, and the quickest-moving of all appeared to be a 5th-magnitude object in the constellation of Cygnus, the Swan. Bayer had not thought it important enough to be given a Greek letter, and it was known as '61 Cygni' because it had been allotted this number by Flamsteed. Its proper motion amounted to just over 5 seconds of arc per annum, which means that it would take over 350 years to shift by a distance equal to the apparent diameter of the Moon, but even so it was exceptionally rapid in its movement—and so presumably was exceptionally near. Moreover it was a binary, the two components being far enough apart to be separated by using a small telescope. This again was some indication of closeness to the Earth.

Bessel was interested. In 1837 he began to search for a parallax shift, and only a year later he was able to prove that both stars of 61 Cygni showed a parallax amounting to 0″·3 (0·3 seconds of arc), giving a distance of almost 11 light-years. Since the modern value is 10·7 light-years, Bessel's estimate was remarkably accurate. Measured in our everyday units, 61 Cygni is roughly 60 million million miles away; to look at it in 1960 means that we are really seeing it as it used to be in 1949.

One-third of a second of arc is a staggeringly small angle, but only a few stars have been found to lie at distances less than that of 61 Cygni, and of course the greater the distance the smaller the parallax shift. Most of the stars are too remote to yield any measurable results at all.

Henderson's selected star was Alpha Centauri, in the southern sky. The choice was a good one; Alpha Centauri's proper motion is comparable with that of 61 Cygni, and it also is a wide binary, though instead of being dim it shines as the brightest star in the heavens apart from Sirius and Canopus. It cannot be seen from Europe, but Henderson was Director of the Cape of Good Hope

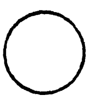


FIG. 8. The smallness of stellar parallaxes. If viewed from a distance of roughly 10 miles, this circle will subtend an angle about equal to that of the annual parallax of Vega, which is one of the closer of the brilliant naked-eye stars. It is hardly surprising that such tiny shifts are extremely difficult to measure.

Observatory, and in 1832 he began his measurements. Unfortunately his health was not good, and he was compelled to retire from the Directorship after a comparatively brief spell of office; he came back to his native Scotland, and did not work out his results for Alpha Centauri until after Bessel's triumph in the case of 61 Cygni. Actually Henderson had rather the easier task, since Alpha Centauri has a parallax of 0″·76, and is the closest of the brilliant stars, with a distance of 4·3 light-years or roughly 25 million million miles. We now know that Proxima, a very faint member of the Alpha Centauri system, is 1/10th of a light-year nearer still, and is our closest stellar neighbour—apart of course from the Sun.

Struve, at Dorpat in Estonia, studied the lovely bluish star Vega, in Lyra. Here the parallax is smaller, because Vega is farther away, and Struve's results were inaccurate; actually Vega is 26 light-years away from us, or more than 150 million million miles. Struve had thus to measure an angle equal to that subtended by a farthing 12 miles away. However, he was at least on the right track.

One more unit of measurement is worth introducing here, because it is always quoted in technical papers. Light-years are quite convenient, but even better is the 'parsec', which is the distance at which a star would yield a parallax of 1 second of arc. It is equal to 3·26 light-years.*

So far, so good; the scale of the star-system had been found, and during the following years other distances were measured with fair accuracy. Unfortunately the small angles due to parallax are always hard to determine, and the whole method is limited to the nearest stars. For distances over 150 light-years it is decidedly untrustworthy, and by 600 light-years the shifts have become so slight that they are utterly swamped by unavoidable errors in observation, so that the system breaks down.

To carry our distance-gauging farther into space, we must therefore make use of less direct methods. The telescope by itself cannot help us, and we have to combine it with other instruments, the most important of which is the spectroscope. This brings us to pure 'astrophysics', or the physics of the stars, but before going into more detail it is worth giving some attention to the various constellation patterns. The stars become far more interesting when you learn to tell which is which.

* We can build up a useful 'multiplication table' here, starting with the astronomical unit or distance between the Earth and the Sun, which in round figures is 93,000,000 miles. Then:

63,000 astronomical units = 1 light-year = 5,880,000,000,000 miles;
3·26 light-years = 1 parsec = 19,150,000,000,000 miles
= 206,000 astronomical units.

It makes a journey from London to Australia seem very trifling!

5

The Constellations

The best method of learning your way around the night sky is to equip yourself with a star-map, go outdoors and pick out the groups one by one. It can be a cold process, particularly in the early hours, but there is no short cut. Fortunately the constellations are not nearly so hard to recognize as might be thought; one soon becomes used to them, and when they have been identified they are easy to find again.

The star-patterns, as we know, do not change except over vast spans of time, but sometimes you will see a starlike object apparently ignored by your map. This will probably be a planet—unless, of course, a high-flying aeroplane is to blame—and it may cause temporary confusion, since it will alter the whole aspect of the constellation in which it lies. It will of course be somewhere in the Zodiac, and its nature should be obvious enough.

Each planet has a 'personality' of its own. Venus may be seen either in the western sky after sunset or in the eastern sky before dawn, and is so much brighter than anything else that it may be identified at once; at maximum, it may even cast a shadow. Jupiter also is extremely brilliant, while Mars is distinguished by its red colour. Saturn, admittedly, does look very like a yellowish star of about the first magnitude, and the only solution is to look up its position before you start observing. The remaining planets are never conspicuous, and for the moment we need not trouble further about them.

This is not the place to give a detailed map of the heavens, and all I propose to do is to indicate the main groups, together with any special objects which will be referred to again later in this book. In any case, the first step must be to learn the main 'sky-marks', just as a visitor to Britain would be well advised to find out the position of London before looking for Clapham Common or West Dulwich.

By no means all the constellations contain any objects of note, and even some of the Zodiacal groups are decidedly dull. Moreover, observers who live in the northern hemisphere are limited; we cannot see stars near the south celestial pole, and this is unfortunate, since we are deprived of regions which contain some of the most fascinating objects in the sky. All this leads us on to some mathematical reckoning which does not actually involve anything more abstruse than ordinary subtraction.

Remember that star declinations are reckoned according to the celestial equator, so that—for instance—Mizar in the Plough has a value of +55°, or 55 degrees north, while Sirius has declination −17° (17 degrees south).* If we know our own latitude on the Earth, we can easily work out which part of the sky we can see; all that has to be done is to subtract our latitude from 90°. Lizard Point, at the southernmost tip of England, has a latitude of +50°. Taking 50 away from 90, we are left with 40; therefore any star north of declination +40° will be circumpolar, while any star south of declination −40° will never rise at all.

Now let us consider one or two of the bright stars. Vega has a declination of +39° (more accurately, +38° 44′) and is therefore not quite circumpolar from the Lizard; it sets for a brief period each day, whereas Capella, with its declination of +46°, is visible all the time. In the opposite part of the sky, several first-magnitude stars are well to the south of our limiting −40°, including Canopus and the famous Alpha Centauri.

Now let us take a trip to the Shetland Isles, where the latitude is +60°. Here our limiting declination will be −30° (since 60 subtracted from 90 equals 30), and stars north of declination +30° will be circumpolar. It is clear that Vega as well as Capella will remain permanently above the horizon, and Pollux will only just dip out of view. On the other hand, look at Fomalhaut, with its declination of almost −30°. It was easily visible from Lizard Point, but from the Shetlands it will only just rise above the horizon, and if there is the slightest trace of mist about (as there usually is) it is not likely to be seen.

* For the purpose of these rough and ready calculations, declinations of stars and the latitudes of observing points on the Earth are given in round numbers. The declination of Mizar, for instance, is actually +55° 11′.

Suppose we want to see the brilliant yellow star Canopus, which is second only to Sirius? We can make our calculation the other way round. The declination of Canopus is −53°; taking 53 away from 90, we are left with 37, so we must go down to latitude 37° north. Gibraltar (latitude +35°) will not quite do, but from Cairo (+30°) Canopus will reach a peak altitude of 7 degrees above the horizon, so that it will be clearly seen.

Those of us who live in Europe or the United States are inclined to have a 'northern complex', so before we begin our tour of the sky let us examine the situation at—say—Melbourne, where the latitude is −38°. The same rules apply. Take 38 from 90; this leaves us with 52, so that stars south of declination −52° will be circumpolar and those north of +52° will never rise. From Melbourne, then, Canopus grazes the horizon when at its lowest; Alpha Centauri and the Southern Cross never set; all the first-magnitude stars in our list will be seen at one time or another. On the other hand we have lost the Plough, since only Alkaid, with its declination of +50°, will peep shyly above the horizon.

These calculations can be made for any declination and any latitude, and it seems that southern observers have the best of things. Near the south celestial pole there are numerous interesting objects, while by contrast the north polar region is rather barren. Those who have seen the whole sky are generally very ready to exchange our Bears, Dragon, and Lynx for the Southern Cross, the Ship, and the Centaur.

For a start, however, let us keep to our northern aspect, and view the skies as they are seen from Britain. Ursa Major, marked by its seven Plough stars, is circumpolar, and is so easy to recognize that it makes a splendid 'signpost'. All the Plough stars have separate names as well as Greek letters; in fact the star at the end of the handle has two names—Alkaid and Benetnasch—as well as its official designation of Eta Ursæ Majoris. It is worth noting that Megrez is fainter than its companions, while Mizar is the famous binary. Alcor, some distance from Mizar itself, is very easy to see with the naked eye except when conditions are ruined by cloud, mist or artificial lights.

Other groups can be found by using the Plough as a guide, and the diagram given here speaks for itself. The Pointers, for instance, lead us to Ursa Minor, which looks a little like a twisted and anæmic version of the Great Bear, but is celebrated because it contains the Pole Star. The magnitude of the Pole Star is about 2, and this is also the case with Kocab, nicknamed the Guardian of the Pole, which is decidedly orange.

Next we can find Cassiopeia—the proud queen who behaved so tactlessly in boasting of her daughter's beauty—and her husband

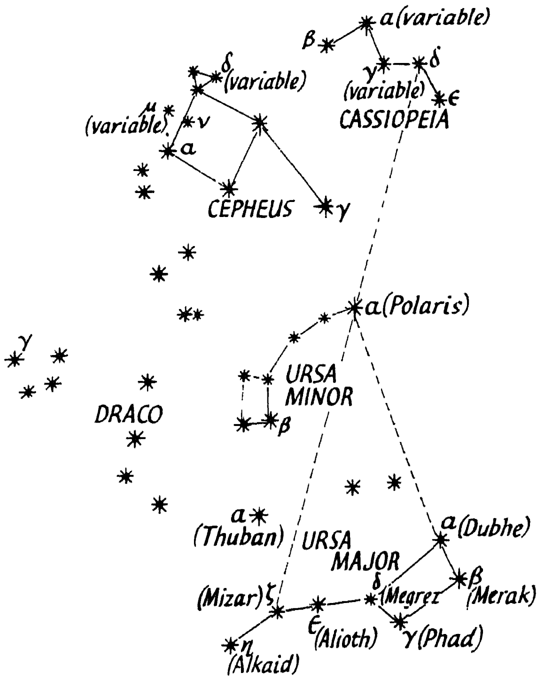


FIG. 9. The northern groups. Note how constellations such as Cepheus and Cassiopeia can be found by using the Plough stars of Ursa Major as a guide.

Cepheus. Cassiopeia is very conspicuous, and the pattern of stars forming a rough W can hardly be missed, but her husband is much more obscure. However, he is notable because he contains a most important star which has played a great part in helping astronomers to measure out the universe. Oddly enough, this star has no special name, and is known only by its official designation of Delta Cephei;

it is variable, but never brighter than Megrez, the feeblest member of the Plough group, so that you will have to look carefully for it.

Now that we have dealt with the main circumpolar groups—remembering that we are speaking from the viewpoint of an observer in Britain—let us go through the seasons, and find out what is to be seen.

Spring evenings: say mid-April at about 9 *p.m.*—The Plough is almost overhead. Following through the 'handle' we come first

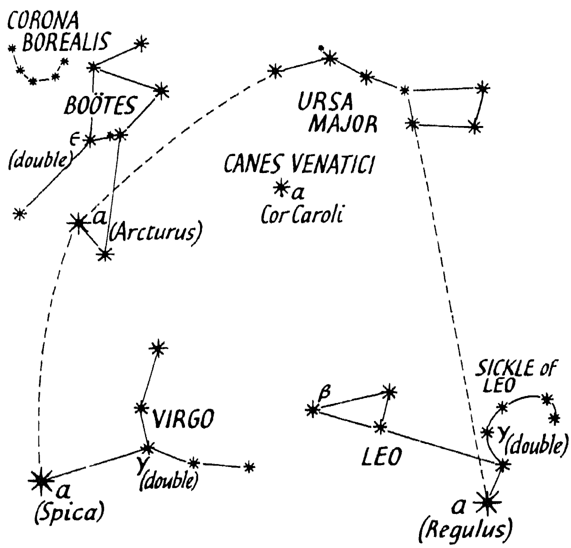


FIG. 10. Some of the constellations well seen in spring. Note the 'curve' from the Plough-handle through to Arcturus in Boötes and Spica in Virgo; also the characteristic Sickle of Leo.

to Arcturus in Boötes, which can hardly be missed, as with the exception of Sirius it is the brightest star ever visible in England; it is also prominent because of its glorious orange hue. The rest of Boötes is rather obscure, but it is worth looking for Corona Borealis, a semi-circlet of stars which really does look rather like a crown. (How anybody could make a herdsman out of Boötes passes all comprehension; the ancients were nothing if not imaginative.)

Following the Plough–Arcturus curve still farther we come to

Virgo, where the leading star, Spica, is bright enough to be easily identified. The Virgin herself takes the form of a distorted Y; note Postvarta, more generally known by Bayer's designation of Gamma Virginis, which any small telescope will show to be a spectacular binary. The components are almost exactly equal, so that here we have a case of true stellar twinning. Not far off is the celestial lion, Leo; Regulus is the chief star, and the Sickle, shaped rather like a question-mark twisted the wrong way round, is distinctive. Algieba or Gamma Leonis is a binary, while the other important star in the constellation, Denebola, is suspected of being variable in brightness.

At this time Capella is to be seen in the western part of the sky and Vega in the eastern; Cassiopeia is in the north, and is at its lowest, though still well above the horizon. Orion has set, but some of the stars forming his brilliant retinue are still to be seen, notably Procyon and the 'heavenly twins' Castor and Pollux.

Summer evenings: say mid-July at 11 *p.m.*—The Plough lies in the west, with Arcturus still visible; Leo and Virgo have gone, and Capella is barely to be seen very low in the north.

Overhead lies Vega, in the small but interesting constellation of Lyra. Vega is almost as brilliant as Arcturus, and is decidedly bluish, so that it is a glorious sight in binoculars or a low-power telescope. Also in this area are Sheliak or Beta Lyræ, a binary of very special type; Epsilon Lyræ, a multiple star, obscure to the naked eye but fascinating when seen through a telescope; and various fainter objects which will be described later.

Vega forms a triangle with two other first-magnitude stars, Altair and Deneb. Altair, in Aquila, is high in the south, and is easy to recognize because it is flanked to either side by a fainter star. The rest of Aquila is distinctive, though not brilliant, and adjoining it is one of the modern groups—Scutum, the Shield, which contains a magnificent star-cluster known popularly as the Wild Duck. Even a small instrument will show that it contains a great many 'birds'.

Deneb is the leader of Cygnus, the Swan. The constellation would be more aptly termed the Northern Cross, as indeed it often is; the X-shape is rather spoiled by the fact that one member, Albireo, is too faint and too far from the centre, but to make up for this Albireo proves to be probably the loveliest double star in the sky. The primary is golden-yellow, the companion bluish-green. I never tire of looking at Albireo through my telescope; no description can do justice to it.

Summer is a good time for looking at the Milky Way, which flows through Cassiopeia, Cygnus, and Aquila down to the

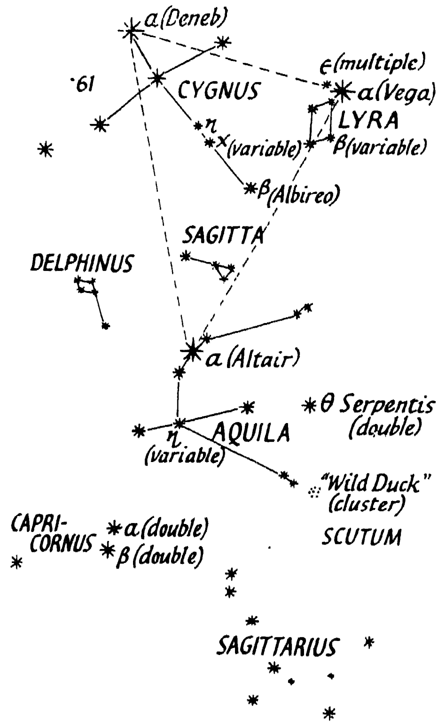


FIG. 11. Some of the summer constellations. The great triangle formed by Vega, Altair, and Deneb is easy to find, and acts as an excellent guide to the other groups.

southern horizon. Another star worthy of note is Antares, in Scorpio, which is strongly red; its very name means 'Rival of Mars'. It is low in the south, and unfortunately we never see it to advantage, while part of Scorpio—which is a splendid constellation—never rises at all in Britain.

The area enclosed by lines joining Arcturus, Vega, and Antares is rather barren, as it is occupied by three large, sprawling constellations—Hercules, the legendary hero; Ophiuchus, the serpent-bearer; and Serpens, the reptile with which he is meant to be struggling. Judging from the old maps the tussle is a fierce one, and Ophiuchus appears to have pulled the Serpent in half.

Autumn evenings: say mid-October at 9 p.m.—This is the least spectacular period of the year from the stellar point of view. The Plough is low in the north, Vega high in the west and Capella easterly; Arcturus, Leo, Antares, and Spica are invisible, and Orion has not yet risen, though Aldebaran in Taurus is well above the eastern horizon. Deneb (which is circumpolar in Britain) and Altair remain prominent.

The southern aspect is dominated by Pegasus, the Flying Horse. Needless to say it looks nothing like a horse, airborne or otherwise, since it takes the form of a square, and is not so conspicuous as might be thought from the map; most people expect it to be smaller and brighter than it really is. Below it, low in the south, is Fomalhaut, the only bright star of Piscis Australis. This is the most southerly of the 1st-magnitude stars visible from Britain, and it barely rises in North Scotland, though from England it can be quite prominent.

Cassiopeia is very high up, and an easy way to find Pegasus is by using two of the W-stars as pointers. We have in fact come to the most famous of all the old sky legends—the story of how Perseus rescued the beautiful maiden Andromeda by petrifying her enemy, the monster Cetus, with the Gorgon's head. All the main characters are to be seen. Andromeda consists of a line of fairly bright stars, and for some curious reason she has laid claim to Alpheratz, in the Square, which used to be known officially as Delta Pegasi, but has now been given a free transfer and has become Alpha Andromedæ. Almaak in Andromeda is a famous binary, but the most celebrated object in the whole group is the Great Spiral, a fuzzy patch barely visible to the naked eye, but which we know to be a galaxy even larger than our own.

Perseus makes himself conspicuous, even though his brightest star (Mirphak) is only of the 2nd magnitude. The Gorgon's head is marked by Algol, the 'Winking Demon', to which we will return later on. It is variable, but normally about as bright as Polaris.

Between Mirphak and Cassiopeia may be seen a misty glow which a telescope reveals as a double cluster of stars.

Cetus, the Whale or Monster, is obscure, and though he takes up a great deal of room there is very little to show for it. However,

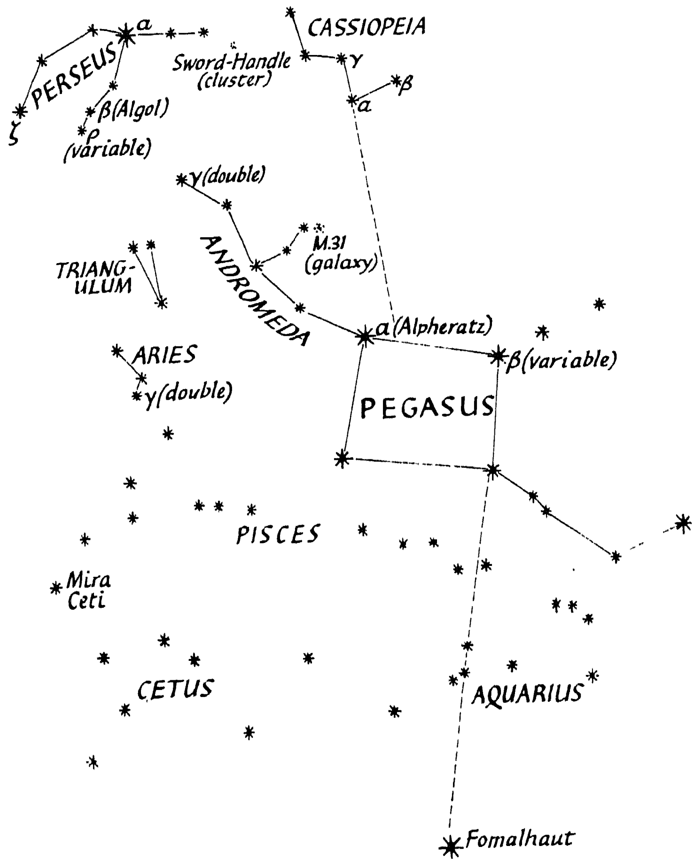


FIG. 12. Autumn constellations: the Square of Pegasus, together with Andromeda, Perseus and other constellations named after characters in the famous legend. Note Fomalhaut, which is the southernmost 1st-magnitude star visible from London or New York.

we must note the famous variable star Mira, which may sometimes attain the 2nd or 3rd magnitude, though more generally it is invisible without a telescope.

Winter evenings: say mid-January at 9 p.m.—The glory of winter skies more than compensates for the relative paucity of autumn. Orion, the most glorious of all constellations, lies in the south, and dominates the scene. Of course our old friends are still visible; the Plough in the north-east, Vega low in the north, Pegasus dropping to the western horizon, Regulus rising in the east, and so on—but all these pale before Orion.

The Hunter's pattern cannot be mistaken. Of his individual stars, the almost pure white Rigel is the most brilliant, and is practically equal to Capella and Vega, though it is much more remote and therefore much more luminous. By contrast Betelgeux* is orange-red, and is variable, though always of the first magnitude. Note also the three stars of the Belt, and the misty Sword which contains the great gaseous nebula.

Orion acts as a splendid guide. In one direction his Belt points to Sirius in Canis Major, which glitters with a lustre far exceeding that of any other star, while in the opposite direction we come to Aldebaran, the Eye of Taurus (the Bull), which is very similar to Betelgeux both in colour and magnitude. In Taurus, too, are two naked-eye clusters; the Hyades, round Aldebaran, and the Pleiades or Seven Sisters. The Pleiades, particularly, form a glorious group, and low-power binoculars give a splendid view of them.

Orion's junior Dog is marked by the 1st-magnitude Procyon, and not far off are Castor and Pollux, the Heavenly Twins who have given their names to the constellation Gemini itself. Here too we have a legend. It is said that of the two brothers, Pollux was immortal, while Castor was not. When the inevitable happened, and Castor was killed, Pollux was so grief-stricken that the Olympians came to the rescue, and placed both youths in the sky. Castor, the fainter of the two, is white—perhaps as a result of his misfortunes!—while Pollux is orange-yellow.

The rest of Gemini is made up of lines of stars stretching from Castor and Pollux in the general direction of Betelgeux. Both Eta

* This name may be spelled in several ways—Betelgeuse and Betelgeuze are other forms. Moreover, nobody seems to know quite how to pronounce it. I refuse to call it 'Beetlejuice', as many people do; the name comes from the Arabic, and an Arab scholar tells me that 'Bay-tell-jurze' is about as near as we can get. The name is a result of several mis-translations, and in its present form means nothing in particular.

and Zeta Geminorum are interesting variables, though neither is brilliant.

Finally let us look at Capella in Auriga, which has taken over the zenith position occupied in summer by Vega. It is a glorious yellow star, and may be described as a much more luminous version

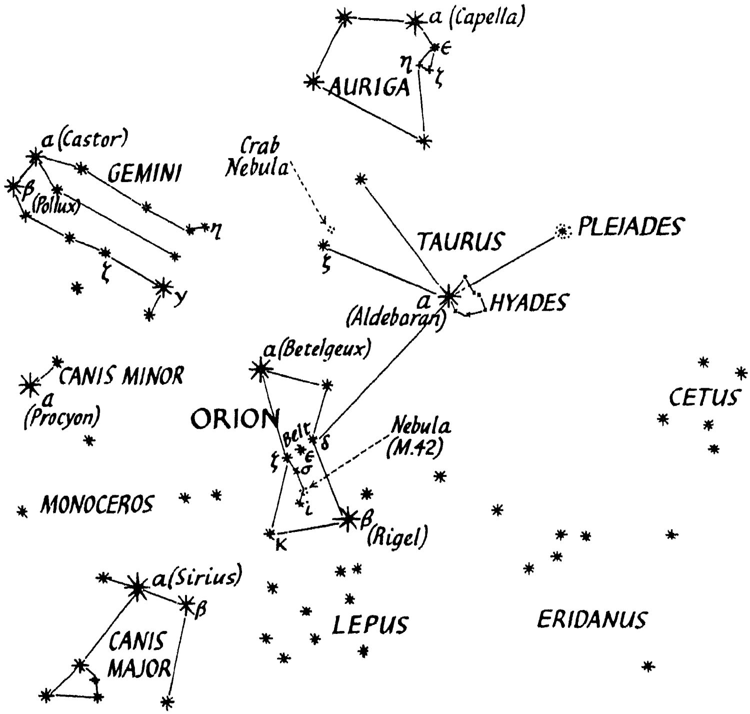


FIG. 13. Winter constellations: Orion and his retinue. Note the brilliant stars Capella, Procyon, Castor and Pollux, Aldebaran and Sirius, as well as the unmistakable figure of Orion himself.

of the Sun, though it differs in being a very close binary. Beside it lies a triangle made up of three faint stars known as the Hædi, or Kids, two of which (Epsilon and Zeta Aurigæ) are veritable giants —they are, indeed, among the largest stars known to us. Auriga is completed by a sort of kite-pattern, and is crossed by the Milky Way.

This 'review of the year' is very sketchy and incomplete, and many groups have not been mentioned at all, but at least it will serve as a basis. Once you have learned how to find the groups given here, the rest will be easy to identify.

Apart from far northern groups such as the Bears, the constellations described above are visible from all the most densely-populated parts of Earth. From lower latitudes, however, we have the advantage of seeing the southern stars as well. Naturally the names are more modern, since the areas concerned were invisible to the old star-cataloguers, and the result is a most peculiar medley.

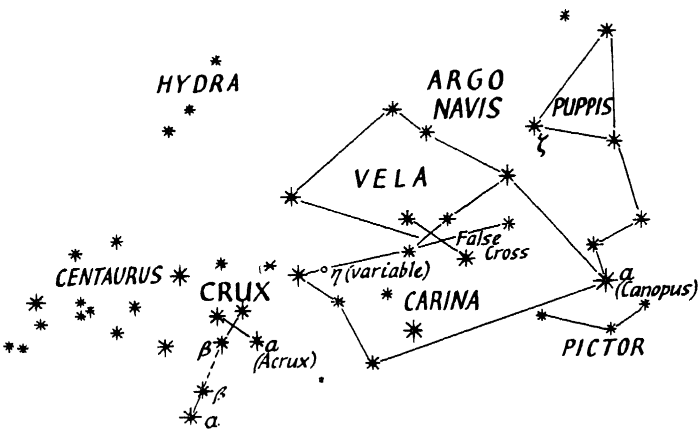


FIG. 14. Southern stars: Argo Navis, Centaurus and the Southern Cross. Note the 'False Cross' in Argo. It is quite easily confused with Crux Australis, but is rather larger, and its stars are not so bright. Alpha and Beta Centauri point to the real Crux.

One region seems to be a kind of aviary, since we have the Crane, the Peacock, the Toucan, and the Phœnix close together, accompanied by such unexpected neighbours as the Indian and the Microscope. But to Australians, New Zealanders and South Africans, the symbol of the sky is the Southern Cross, which is as familiar to them as the Plough is to Londoners and New Yorkers.

Crux Australis, to give it its Latin title, has the distinction of being the smallest constellation in the sky. Nevertheless it is very prominent, as it contains two 1st-magnitude stars (Acrux and Beta Crucis), one of the 2nd, and one just below the 3rd. Again it is more like a kite than a cross, but those who have seen it tell me that it is quite unmistakable. Not far off is Centaurus, again with two really brilliant stars—one of which, Alpha Centauri, is only just over 4 light-years away from us; moreover it is a splendid binary, and together the two components outshine even Arcturus. In the same general region is Argo, the ship which carried Jason on his quest of the Golden Fleece, headed by Canopus, which is inferior only to Sirius.

In one respect northerners have the advantage. There is no bright south pole star, and the present holder of the title, Sigma Octantis, is very dim indeed. However, the presence of the two Nubeculæ or Magellanic Clouds, named after the explorer Magellan, provides ample compensation; they look like detached parts of the Milky Way, and the Larger Cloud remains visible to the naked eye even in strong moonlight. Neither must we forget Achernar, the 'Last of the River', which is almost as bright as Procyon.

We can see that there is endless variety above us, so that whether we live in London or Sydney, New York or Tierra del Fuego, the night skies provide an ever-changing panorama which never palls. Now that the main constellations have been described, it is time for us to return to our main theme, and see whether we can decide what a star is really like.

6

The Message of Starlight

In 1825 a Frenchman, Auguste Comte, wrote a book called *Cours de Philosophie Positive* in which he made a profound statement. Some things, he said, are destined to remain permanently unknown to mankind; and as an excellent example he cited the chemistry of the stars. According to Comte, it was absolutely impossible to find out 'what stars are made of'.

Other statements of like nature have been shown to be equally wrong. In 1840 Dr. Dionysius Lardner, addressing the British Association, gave his opinion that 'men might as well try to reach the Moon as attempt to cross the stormy North Atlantic Ocean by means of steam power', while in the same year Arago, a leading French astronomer, repeated Herschel's view that the Sun is inhabited.

Some people are credulous enough to believe almost anything. The modern flying saucer craze is a case in point; weird stories about men from Venus, who land in their space-craft and mingle freely with us in order to distribute sweetness and light in all directions, have been headline news at regular intervals ever since 1947. Even to the Flying Saucerers, however, the idea of a habitable Sun must seem a little odd, and the fact that so great an astronomer as Herschel believed in it is a pointer to the paucity of our knowledge a century and a half ago. Of course Herschel realized that the Sun is hot, but he believed that below the brilliant surface there might be a cool, cloudy region peopled by men.

Auguste Comte's statement was far too dogmatic. There are ways of studying the chemistry of the stars without actually travelling to them, and the first step had been taken by Sir Isaac Newton more than 150 years before Comte's time.

In 1666 Newton, then young and unknown, was residing at his home at Woolsthorpe in Lincolnshire; he had temporarily left Cambridge because of the Great Plague, which had resulted in the very wise decision to close the University until the danger was over. At Woolsthorpe, Newton busied himself in laying the foundations for much of his later work. Some of his main studies concerned the nature of light.

One reason for this interest was that he was anxious to build better telescopes. Up to then all telescopes had been of the refracting type, and were not satisfactory because of the false colour problem. Newton determined to find out just why this false colour appeared.

What he did was to make a hole in an opaque blind, and admit a beam of sunlight, which he then passed through a glass prism. Upon emerging from the prism, the light was spread out into a

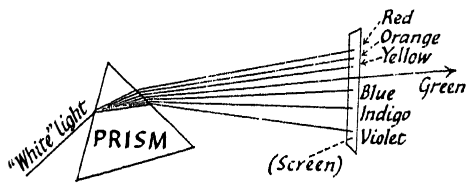


FIG. 15. The composite nature of light. If 'white' light from a source such as the Sun is passed through a prism, it is split up into its constituent colours, and the result is a rainbow—a continuous spectrum. In Newton's classic experiment, sunlight was passed through a prism, and then a single colour (green) was passed through a second prism. This time there was no rainbow; the green light was not further split up.

rainbow, from red at one end of the band to violet at the other. Newton then placed a second screen with a hole to admit the light of one colour only, and passed this one colour through another prism. This time there was no rainbow. The ray was slightly bent or 'refracted', but it remained the same colour as before.

This gave Newton the key to the whole situation. Sunlight, like all so-called 'white' light, is really a mixture of all the colours of the rainbow, and the glass prism splits it up. The violet part of the mixture is refracted more sharply than the blue, the blue more than the yellow, and so on until we reach red, which is refracted least of all. Consequently, the different colours are spread out to give the luminous band or 'spectrum'. In the case of a single colour, of course, no such effect will be seen, since we are no longer dealing with a mixture.

This explained the cause of the false colour which had so puzzled early workers. A refractor's object-glass bears some resemblance to a prism in that it bends the different parts of the mixture unequally, so that blue light is brought to focus closer to the object-glass than in the case of red light. Newton saw no way round the difficulty. He therefore abandoned refractors altogether, and built the first telescope of the reflecting type. Here there was no false colour, since a mirror reflects all parts of the mixture by the same amount.

This was as far as Newton went. He did not realize that object-glasses can be improved by making them compound, and neither did he follow up his studies of the Sun's spectrum. Even his theory

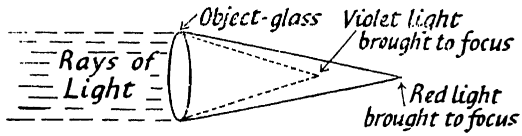


FIG. 16. False colour in early refractors. The object-glass acts rather in the manner of the prism, and refracts violet light more than red, so that different parts of 'white' light are brought to focus in different places. For the sake of clarity, the difference as shown in the diagram is exaggerated.

of light was strongly criticized, and some of the correspondence of that period is not without its humorous side. In Volume 10 of the *Philosophical Transactions* of the Royal Society, for instance, we find the following entry: 'A Letter of Mr. Franc. Linus, written to the Publishers from Liège on the 25th of Febr. 1675, being a Reply to the letter printed in Numb. 110, by way of Answer to a former letter of the same Mr. Linus, concerning Mr. Isaac Newton's Theory of Light and Colors.' On the next page appears 'Mr. Isaac Newton's Considerations on the former Reply' . . . and so on. Tempers on both sides became frayed. Newton, the greatest genius of his age and perhaps of any age, seemed fated to become involved in quarrels; we have to admit that he was sensitive and intolerant of criticism, though on balance he was far more sinned against than sinning.

Little more work on the solar spectrum was done for many years, but in 1802 an English physicist, W. H. Wollaston, repeated Newton's experiment, attaching a 'spectroscope' to the eye-end of a telescope. He noted seven dark lines crossing the coloured band, but he thought that these lines simply marked the boundaries of the various hues—and in consequence missed the chance of making a great discovery. This honour was left to a young German named Joseph von Fraunhofer.

Fraunhofer was born at Straubing, in Bavaria. Both his parents died while he was still a boy, and his schooling was very fragmentary. At the age of fourteen he was apprenticed to a Munich looking-glass maker, one Weichselberger. We often hear tales about cruel taskmasters and starving, ill-treated apprentices, but in Fraunhofer's case the description fitted the facts. Then, one day, the tumbledown house in which he lodged collapsed in a heap of ruins; the accident was seen by the Elector of Bavaria, who happened to be driving by, and the Elector took it into his head to befriend the boy, who had been injured. He gave Fraunhofer enough money for him to buy his release from Weichselberger, and take up the study of optics.

Fraunhofer's ability soon showed itself. In 1806 he obtained a post at the Optical and Physical Institute at Munich, and his reputation spread. He constructed a special instrument known as a heliometer, used by Bessel to determine the distance of 61 Cygni years later, and he became Director of the Institute in 1823, though unfortunately he died three years later at the early age of 40. He also made a 9½-inch object-glass, the largest of its time, which was bought by the Russian Government and installed at Dorpat in Estonia; the telescope was clock-driven, another development which was revolutionary. F. G. W. Struve's main work, including his measurement of the parallax of Vega, was carried out at Dorpat.*

About 1814 Fraunhofer began the research for which he is now best remembered. Like Wollaston, he attached a spectroscope to the eye-end of a telescope, and re-observed the mysterious dark lines in the solar rainbow. His instruments were so much better than Wollaston's that instead of seeing only seven lines, he could make

* I once gave a talk about Fraunhofer to a preparatory school audience. Afterwards one of the boys wrote an essay about it, and produced the following gem which, believe it or not, is authentic: 'Frownhoffer was a very clever man. He was born an orphan, and made a big telescope which he used to measure the distance of a star. He was able to do this because he mounted it on a Doormat.'

out several hundreds; evidently they did not merely mark the boundaries between different colours, but were far more significant.

Fraunhofer was deeply interested. He realized that the lines were fixed and constant; for instance, a prominent double line in the yellow part of the band was always present, and he wondered whether it might be connected with the element sodium, since luminous sodium vapour shows a *bright* double line of yellow hue. Having charted 574 lines in the solar spectrum, he turned his attention to the stars, and obtained equally fascinating results. Here too the general effect was of a rainbow band crossed by dark lines, but in some cases the familiar solar lines were lacking, while new ones appeared in different positions along the band.

We cannot tell how far Fraunhofer would have carried his work; his early death was a blow to science, and for a quarter of a century the dark lines remained unexplained. The problem was solved in 1859 by Gustav Kirchhoff, Professor of Physics at the German university of Heidelberg, who laid down the three fundamental laws which still bear his name. These laws are so important that they must be considered in slightly more detail.

The first law is easy enough. It states that incandescent solids, and also incandescent gases under high pressure, produce a 'continuous' spectrum—that is to say, a rainbow band.

The second law states that a luminous gas or vapour under low pressure will produce an entirely different effect. Instead of a continuous strip, there will be various isolated bright lines—and each line will be the trade-mark of some particular element or group of elements. The effect is known as an 'emission' spectrum.

Matter is made up of atoms, which combine into groups or molecules. There are only 92 different types of atoms which occur naturally, and these are the elements; hydrogen, oxygen, iron, and tin are typical examples. All material is made up of these 92 fundamental substances, and we may be sure that no elements remain to be discovered, since they form a definite series. For instance, a molecule of water consists of two hydrogen atoms combined with one atom of oxygen (hence the chemical formula H_2O), while the molecule of salt is made up of one sodium atom together with one atom of another element, chlorine.

Now let us go back to the second Kirchhoff law, and consider the famous double line which had so interested Fraunhofer. Luminous sodium vapour produces this line; no other element can do so—and in consequence whenever we see the double yellow line, we know that sodium must be responsible. It is the copyright of sodium, and sodium alone.

Each element produces a whole series of lines. Some elements are more prolific than others, iron, particularly, yielding hundreds of lines, but since no two lines exactly coincide it is theoretically possible to disentangle one element from another.

The heart of the dark-line problem is Kirchhoff's third law, and the best way to explain it is to picture a simple experiment. If you burn salt in a flame, you will produce sodium vapour, which will of course yield an emission spectrum containing the double yellow line.* If you look at the spectrum of an electric light bulb, you will find a continuous band, since the filament of the bulb is an incandescent solid (Law 1). Now take the bulb and put it behind the flame, so that you are looking at the emission spectrum of the sodium against the background of the continuous spectrum produced by the bulb. Instead of a rainbow with bright sodium lines superimposed upon it, what you will see takes the form of a rainbow crossed by *dark* lines. In fact, the atoms in the sodium vapour are removing part of the corresponding portion of the continuous spectrum, which is why the dark streaks are known as Absorption Lines.

The crux of the matter is that the positions of the lines are quite unaffected, and this in itself means that they can be tracked down to the elements responsible for them. As soon as you remove the background bulb, the sodium lines become brilliant once more. Incidentally, even in the absorption spectrum they are never properly black; they emit a good deal of light, but seem dark against the rainbow background.

Such were Kirchhoff's laws. Now let us apply them to the Sun.

The principle is exactly the same. In the background we have our 'bulb'—that is to say the Sun's bright surface, which yields a

* There will be many other lines as well, since common salt contains chlorine as well as sodium—not to mention various impurities; but for the sake of the present argument we need consider only the sodium spectrum.

rainbow. In front we have the 'flame', represented by the shell of luminous gas above the solar surface. This shell, or chromosphere, contains incandescent sodium, and so the double yellow line, together with all the other features of the sodium spectrum, appears dark. Here is positive proof that there is sodium in the Sun's chromosphere. Comte was wrong after all!

Nowdays some 70 of the 92 elements have been identified in the Sun, and one story is worth quoting in this connection, since it gives extra proof that astronomy is far from being the abstract, impractical science which so many people still imagine. In 1869 the British astronomer Norman (afterwards Sir Norman) Lockyer was examining the spectrum of the Sun when he noted that one line in the orange-yellow region did not correspond with any element known at the time. He suggested that it might be due to an unknown element, and proposed to name it helium, from the Greek word for 'sun'. A quarter of a century later another Briton, Ramsay, discovered helium on the Earth; it proved to be the lightest of all elements apart from hydrogen, and it plays a great part in astrophysical studies. It differs from hydrogen in being non-inflammable, and for this reason it was once used for filling the gasbags of airships.

The Sun is much the nearest of the stars, and so its spectrum may be studied in great detail. Normally the astronomer's cry is for 'More light!' and for this reason great telescopes are built to collect as much light as possible; but in the case of the Sun there is no such difficulty. Stellar spectra present problems of a different order, since even with the brightest stars there is not enough light to spread out the spectrum to a great length. Fraunhofer, of course, made a start; he was followed by men such as Secchi, a Jesuit priest who examined the spectra of 4000 stars between 1864 and 1868, and Sir William Huggins, who established a private observatory at Tulse Hill and concentrated upon very precise studies of the spectra of certain individual stars. Secchi and Huggins were in turn followed by E. C. Pickering, who worked at the Harvard College Observatory in America.

Gradually some concrete facts emerged. The spectra of different stars were by no means alike; some closely resembled the Sun, while others were utterly different. This was bound up with the colour of the star concerned, and hence with its surface temperature.

The most casual observer can tell that the stars differ in hue. Betelgeux, Antares, and Aldebaran are reddish, Arcturus orange, Capella and Canopus yellowish, Rigel and Sirius white, and Vega bluish. Binoculars or telescopes bring out these colours to advantage, and it is found that some faint stars are even more vivid; Mu Cephei, the irregular variable described in Chapter 10, was described by Herschel as 'garnet', and does indeed look like a glowing coal, while with some binaries the true hues are enhanced by contrast—Beta Cygni being an outstanding example. We know that 'white heat' is greater than 'red heat', and so it is natural to assume that stars such as Rigel are hotter than reddish objects such as Betelgeux.

Secchi divided the stars into four spectral classes. His nomenclature formed a useful basis, but since it is now obsolete there is no point in saying much about it except that Type I was made up of white stars, II of yellow or orange, and III and IV of red.

In 1890 Pickering, at Harvard, introduced a more detailed system, modifications of which have stood the test of time. The general idea was to divide the stars into spectral groups and letter them A, B, C, D and so on, beginning with white stars and working through yellow, orange and orange-red to red. As usually happens, the letters soon became out of order; Types C, D, and E proved to be redundant, and the final result was alphabetically chaotic, so that the modern 'spectrum alphabet' for the stars is as follows: W, O, B, A, F, G, K, M, R, N, S. The mnemonic 'Wow! Oh Be A Fine Girl Kiss Me Right Now Sweetie' is well known; a certain amount of mild amusement may be gained from deriving others!

At least the series is logical in one respect, since it forms a true sequence. In the white A-type stars, for instance, the spectrum lines due to hydrogen are very prominent; they are less intense in the next type (F), fainter still in G, and very inconspicuous in K. This does not necessarily indicate that K-stars contain less hydrogen than those of Type A, but merely that conditions are not so suitable for the hydrogen to show itself.

Each type is divided up into sub-classes, usually numbered from nought to 9. To take part of the order at random, beginning with (say) A0, we have A1, A2, A3 . . . A9, F0 and so on. A star which is midway in type between A0 and F0 will therefore be classed as A5; there is very little difference between B9 and A0, or between A9 and F0. When we remember the complexity of stellar spectra, and the difficulties of studying them, it is obvious that a great deal of work has gone into this classification. The early workers such as Secchi had to carry out all their work by means of visual observation at the eye-end of a telescope; nowadays spectra of even faint stars may be photographed and studied at leisure. It is not necessary to use colour photography, since the positions of the lines are sufficient, but even so the task is Herculean.

It may be useful to give a few lines to each type of star, and see just where the main differences lie, though of course any such outline is bound to be hopelessly sketchy. Let us begin, therefore, with the hottest stars—which should logically be given the letter A, but which are in fact allotted W.

W stars.—These are almost in the nature of celestial freaks, since they show rainbow backgrounds crossed by many lines which are bright instead of dark. Though very luminous, they are also very distant, and none shine brilliantly in our skies. We will return to them later. Allied to Class W are the *O stars*, greenish-white and also intensely hot, with surface temperatures of some 35,000° C., and with both bright and dark lines in their spectra. A typical example is Zeta Argûs (O5). W and O stars are often termed Wolf-Rayet stars, in honour of two astronomers who paid particular attention to them, but strictly speaking the term should be confined to Type W.

B stars.—These are bluish-white, and have surface temperatures of up to 25,000 degrees. Helium is very prominent in their spectra, and they are therefore often known as 'helium stars'; hydrogen lines are also prominent. Typical specimens are Epsilon Orionis, in the hunter's belt (B0); Kappa Orionis (also B0) and Alkaid in the Plough (B3). Rigel is often cited as a typical B-star, but it is not a good example. It is of exceptionally high luminosity, which affects the spectrum, and in any case it is classed as B8, so that it is not far off Type A.

A stars.—Known commonly as Sirian stars, since Sirius is of this type (A1); other examples are Vega (A0) and Altair (A7). The stars are white, and their spectra are dominated by hydrogen lines. Average A stars have surface temperatures in the region of 11,000 degrees, and are much more luminous than the Sun.

F stars.—Yellowish, with surfaces which are less hot; the temperatures are around 7500 degrees. Hydrogen is weaker than in Type A, but calcium lines are strong. Note two calcium lines lettered H and K.* Typical F stars are Beta Cassiopeiæ (F3), Procyon (F5) and Polaris (F8). The brilliant southern Canopus is classed as F0, but it too is exceptionally luminous, and its spectrum has peculiarities.

G stars.—Known as Solar stars, since the class includes our own Sun. Hydrogen lines continue to weaken, and lines due to metals are stronger. After G5 we start to meet with lines produced by molecules, and this is an indication of lower surface temperature, since the great heat of earlier types prevents molecules from being formed at all—they would at once be broken up into their component atoms. G stars are yellow, and have temperatures of around 6000 degrees. Other examples are Capella (G0) and the brighter star of the Alpha Centauri pair (G2).

K stars.—These are orange, with surface temperatures of about 4200 degrees. Metallic lines are becoming strong, with hydrogen much weaker; the H and K lines of calcium are still evident, but less so than in Type G. The most brilliant example is Arcturus (K0), and in consequence these are often known as Arcturian stars. Others are Kocab in Ursa Minor (K4) and Aldebaran (K5).

M stars.—Here we come to very complicated spectra, with many bands due to molecules. Titanium oxide is particularly prominent, and calcium is also much in evidence. The surface temperatures are in the order of 3000 degrees, and the general colour is orange or orange-red. Typical examples are Antares (M1) and Betelgeux (M2), while Proxima Centauri, the nearest of all stars apart from the Sun, also yields an M spectrum. It is worth noting that many stars of this type are variable in brilliancy.

N, R, and S stars.—All these are red and remote, so that they appear dim in our skies. N objects are known as 'carbon stars', since lines due to this element are so prominent; R stars are somewhat

* Logically, a hydrogen line should be given the letter H; but as is so often the case, logic has been subordinated to custom.

similar, while Type S is made up chiefly of variable stars. For subdivisions, small letters are used instead of figures. The reddest of all stars, such as the telescopic variable S Cephei, belong to type Nc.

Listed in this way the differences between the various types may seem obvious enough, but anyone who has looked at a stellar spectrum will appreciate the problems involved, and the photographs following page 128 may indicate the difficulties. To make matters even more complex, not all stars can be put into neat, compact classes. The extraordinary White Dwarfs, for instance—about which more will be said later—reveal almost nothing apart from a few broad hydrogen lines; also there are the shell-stars, whose vast gaseous surrounds produce emission lines superimposed on a rainbow background, and so on. The 'variations on a theme' seem almost endless.

In any case, the division of the stars into these various types is only a beginning, and an amazing amount of information has been gained from studies of stellar spectra since those far-off days when Fraunhofer first observed the dark absorption lines. For instance, estimates have been made of star-distances. By studies of spectra, it often happens that the luminosity ratio between two stars may be found, and this gives an immediate clue. Suppose that we have two stars A and B, A being close enough to show measurable parallax while B is not, and that we know how much more (or less) luminous B is than A. Our knowledge of A's distance then leads us on to that of B.

More important still, we have a tool which can help us to probe the real natures of these other suns. The message of starlight has at last started to make sense to us.

7

A Star's Surface and Surroundings

We can measure the temperatures of the stars. The different colours give us some clue, since it is clear that a bluish star such as Vega must be hotter than the yellow Capella or the orange-red Betelgeux, but we can be much more precise than this. Spectroscopic work allows us to fix stellar surface temperatures with pleasing accuracy, and we are justified in giving values correct to within a few hundreds of degrees.

Yet we cannot look closely on to a star's surface to see what is happening there. No disks are visible, and there is a limit to what we can find out simply by staring at a twinkling point. Fortunately this does not apply to the Sun, and so if we are to make intelligent guesses as to the nature of star-surfaces we must first see what solar workers can tell us.

The crux of the whole situation is that the Sun is perfectly normal, so far as we know. There is nothing to mark it out from its fellows, and so its surface features are likely to be quite conventional. Instead of a luminous dot we are presented with a blazing disk, ready for our inspection, and there is as much light as any astronomer could want; in fact the amount of radiation which we receive is so great that the Sun has to be observed with special equipment. Here, at least, we do not need vast reflectors such as the Palomar 200-inch.

To look straight at the Sun through any telescope, or even a pair of low-power opera-glasses, is foolhardy in the extreme. The lens (or mirror, as the case may be) will act as a burning-glass, and the entire radiation will be focused upon your eye. Permanent blindness will probably result, and even a second's exposure to the focused light is enough to lead to tragedy. This is the case even when the Sun shines with deceptive gentleness through a layer of mist or fog; no safeguards are adequate.

Regrettably, it is possible to buy dark 'sun-caps', which—so their makers claim—make direct observation safe; it is said that once a dark lens has been screwed over the telescope eyepiece, the Sun's light is reduced so drastically that there is no danger in looking straight at it. I can only say that I do not agree, and would welcome a complete manufacturing ban upon all such devices. A dark glass is always liable to splinter without warning, and anyone who uses one is running a real risk.

The sensible way to look at the Sun is by projection. First point the telescope in the right direction, keeping a cover over the object-glass; then remove the cover, and allow the Sun's image to fall upon a piece of white paper or card. The resulting view will be quite satisfactory, and so long as you keep your eye well away

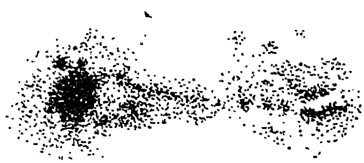


FIG. 17. A typical sunspot group; note the dark 'umbra' and the lighter surrounding 'penumbra'.

from the eyepiece there is no danger at all. For casual 'sun-gazing' a small refractor is ideal. Reflectors are not so suitable, and an instrument with—say—a 6-inch mirror will collect much more light than is required.

When the Sun appears upon your improvised screen, the disk will be seen to appear sharply-bounded. This bright surface, known as the Photosphere, is at a temperature of around 6000 degrees, which is quite normal for a G-type star, but it will often be seen that there are darker patches on it here and there. These sunspots, first observed telescopically by Galileo and his contemporaries three and a half centuries ago, are not so black as they look. They send out a great deal of radiation, but they appear dark because their temperatures are decidedly lower than that of the surrounding photosphere.

Sunspots are not permanent. A small one may last for only a few hours or a few days, and even the present holder of the persistence record, a large spot seen during 1943, had a lifetime of less than a year. On the other hand they may sometimes cover vast areas, and I well remember the great spot-group of April 1947, which at maximum covered an area of over 7 million square miles of the Sun's surface. In January 1959 a comparable group made its appearance, and was easily visible without a telescope when the sunlight passed through atmospheric smoke or mist.

Sunspots have been closely studied, but their exact cause is still uncertain, and though we have found out how they behave we do not know their true significance. They are interesting to watch, even though the amateur astronomer cannot hope to carry out

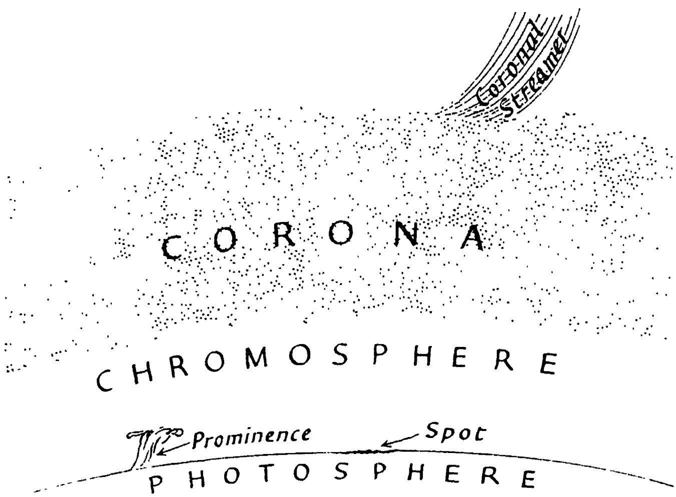


FIG. 18. The Sun's surface and surroundings. The photosphere is succeeded by the chromosphere, which acts as a 'reversing layer' and is responsible for the Fraunhofer dark lines. It is also the region where prominences and flares occur. Beyond the chromosphere comes the much more tenuous and extensive corona. Since the Sun is in no way abnormal, it is reasonable to suppose that other stars of similar spectral type follow the same general pattern.

useful observations of them, and it is also well worth looking for the faculæ, bright areas usually—though not invariably—associated with spot groups.

The whole photosphere appears to be in constant motion, as indeed is only to be expected in view of the fact that it is made up of extremely hot gas. Larger telescopes used under good conditions reveal a mottled appearance known as granulation; the separate granules are, on an average, about a thousand miles in diameter, and have upward motions of over half a mile per second. The Sun's surface is never calm.

As we have seen, the bright surface of the Sun is overlaid by a gas-layer, the chromosphere, which produces the dark Fraunhofer lines. Beyond the chromosphere we come to the corona, a very extended mantle of tenuous gas. Occasionally both chromosphere and corona may be seen with the unaided eye; this is the case when the Moon passes between ourselves and the Sun, blotting out the dazzling photosphere and producing a total solar eclipse.

The theory of an eclipse is easy to understand. By a strange coincidence—so far as we know, it is nothing more—the Moon and the Sun appear almost exactly the same size in the sky, so that when the lining-up is perfect the Moon's shadow touches the Earth. As the last sliver of photosphere vanishes, the corona and chromo-

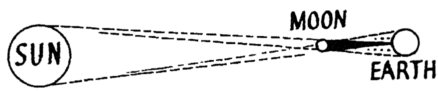


FIG. 19. Theory of a total solar eclipse. To either side of the narrow belt of totality, the Sun will appear partially eclipsed.

sphere flash into view, giving an effect which is indescribably beautiful. Also to be seen are the prominences, often known by the misleading nickname of 'red flames'. It is a pity that total eclipses can never last for more than a few minutes, and that they are comparatively rare. The eclipse of June 30, 1954 was just total off the north Scottish islands, but only partial in England; we must wait until 1999 for the next total solar eclipse visible from anywhere in our islands.

The chromosphere is a particularly important region. Not only is it responsible for the Fraunhofer lines, but it is also the zone in which we meet with solar 'flares', which may be described as storms of an electrical nature. Only very rarely may a flare be seen by ordinary telescopic observation, but instruments based upon the principle of the spectroscope allow astronomers to study them without difficulty. Flares are generally associated with active sun-spots, and have marked effects upon our compass needles, so that we can tell at once that they are strong emitters of radiation.

Now let us see how closely we are entitled to compare the Sun with other stars.

It is appropriate to begin with Alpha Centauri, the closest of the bright stars. It is a binary, as any small telescope will show, but for the moment we will consider only the senior component, which has a G-type spectrum. The surface temperature is almost exactly the same as the Sun's, while the diameter also is of the same order as that of the Sun (about 865,000 miles), and the mass and luminosity are very slightly greater. The star is, therefore, strikingly like the Sun.

Not all G-type stars are the same. Capella has a similar spectrum, but here the diameter is over 10 million miles, and Capella shines with a luminosity equal to 150 Suns put together. If we reckon the Sun as being an 'ordinary' G star, then Capella must be classed as a giant. Yet its mass is only just over four times that of the Sun, so that the material making up its vast globe must be less dense.

Turning to stars of later spectral type (K and M), we find that the range in size and luminosity is even greater. The brighter component of the 61 Cygni pair shows a K spectrum, and so does the brilliant orange Arcturus, but there is little outward resemblance between the two except inasmuch as their surface temperatures are roughly the same. 61 Cygni has a diameter of 600,000 miles and a luminosity of 6/100, taking the Sun as unity; Arcturus is 26 million miles across and 100 times as luminous as the Sun. Here we have a K dwarf and a K giant, and here again the dwarf is much the denser of the two. Arcturus is only about 16 times as massive as 61 Cygni, despite the tremendous difference in size and brilliancy.

In the case of M stars we find that we meet either with true giants, such as Betelgeux (diameter 250 million miles) or with dwarfs much smaller and feebler than the Sun, while stars which have an M-type spectrum and a diameter and luminosity the same as the Sun's simply do not exist, no matter how hard we search for them. Moreover, the giants are very rarefied; the mean density of Betelgeux is only 0·000006 that of the Sun, so that the outer layers, at least, are immensely more tenuous than the air we breathe. Actually, the mass of Betelgeux is only 15 times greater than the Sun's.

What of the much hotter stars showing spectra of types B and A?

Here we find no such giant and dwarf division. Of course, not all the very hot stars are equal in luminosity and size, and there is a considerable range, but there are no clear-cut classes. The separation into giants and dwarfs begins to become evident in type F,

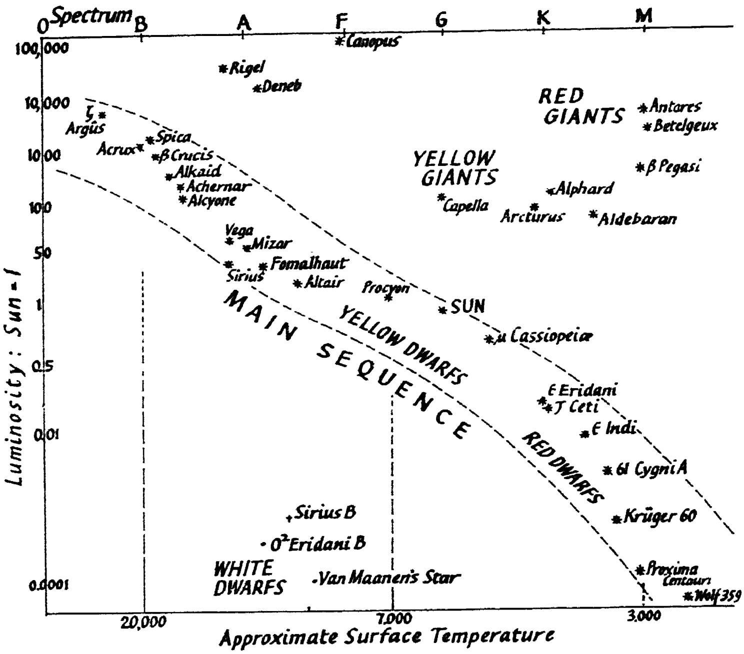


FIG. 20. Spectrum and luminosity. This is a rough chart based upon the principle of the 'Hertzsprung-Russell Diagram', which linked the luminosity of a star with its spectrum type. The division of the red and yellow stars into Giants and Dwarfs is clearly shown. The luminosities of the stars have a tremendous range, and are given here from 100,000 times that of the Sun down to only 0·0001; but it is difficult to fit this range on to a single chart, and the result is bound to be somewhat misleading in this respect, though the principle of the Hertzsprung-Russell Diagram is shown unmistakably. The luminosities of some of the very remote and luminous stars, such as Canopus and Rigel, are hard to determine accurately, and different authorities give different values.

so that we may make a diagram showing the general trend—as shown here. Strictly speaking, the Sun must be classed among the dwarfs; so also must Alpha Centauri, while Capella, with the same sort of spectrum, ranks as a giant.

We have no means of telling whether other stars show spots like those of the Sun. There is no reason to doubt it, at least for stars with solar-type spectra, but definite proof is lacking. On the other hand we can show unmistakably that flares occur.

As we know, a flare on the Sun takes the form of a sudden brilliant patch which appears, usually near or over a spot, and lasts for only a brief period before fading away again. Occasionally a flare may become bright enough to be seen visually—the first recorded case being that of 1859, seen by two pioneer solar workers

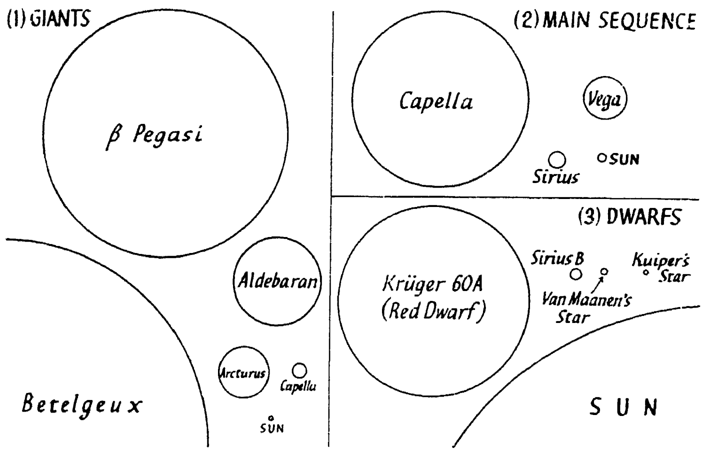


FIG. 21. Sizes of some stars. The first diagram shows two M-type red giants (Beta Pegasi and Betelgeux); two K-type giants (Aldebaran and Arcturus) and a G-type giant (Capella), together with the Sun for comparison. In the second diagram, to a different scale, the Main Sequence stars Sirius, Vega, and the Sun are shown together with one giant (Capella); in the third diagram, again to a different scale, the Sun is shown against one typical M-type Red Dwarf (Krüger 60 A) and three White Dwarfs (Sirius B, Van Maanen's Star and Kuiper's Star).

named Carrington and Hodgson—but it is so small compared with the Sun as a whole that there is no measurable difference in the total output of light. An observer watching the Sun from the distance of, say, Sirius would be unable to tell that an outburst had occurred at all.

In the cases of red dwarf stars (M-type spectra), which are relatively feeble, the situation is different. Here a flare may cause an obvious increase in total luminosity, and of course this increase will be short-lived. The most striking observation so far published was made in 1952 by a Russian astronomer, V. Oskanjan, who was watching the red dwarf star UV Ceti when he saw it brighten up by six magnitudes in the space of *less than one minute*. During the next two or three hours it faded, until it had become normal once more. This was not the first time that UV Ceti had been seen to show sudden bursts, and similar effects have been seen with other red dwarfs, including our nearest stellar neighbour Proxima Centauri.

There seems a good chance that these outbursts are due to flares taking place presumably in the chromospheres of the stars, and this is an extra proof that the Sun is in no way abnormal. Flares in more luminous stars cannot be observed, because they do not make enough difference to the total light emitted, but probably they do exist.

We are building up a fairly reliable picture. The Sun has a bright surface disturbed by relatively short-lived spots; covering the surface is the chromosphere, which acts as a reversing layer to produce the Fraunhofer lines and is also the region in which flares and prominences occur; beyond the chromosphere lies the tenuous, extensive corona. Other stars appear to be built upon the same pattern, though differences in surface temperature mean that conditions are not always the same. The more we learn, the more we have to depart from Auguste Comte's dictum.

On the other hand we also meet with some extraordinary objects which have peculiarities all their own. There are for instance the Wolf-Rayet stars, which yield spectra entirely different from that of the Sun. Instead of absorption lines, we are faced with a series of bright lines, with the ordinary Fraunhofer effect relegated to a very minor rôle.

The story of these stars goes back to 1867, when the first three were recognized by G. Wolf and G. Rayet at the Paris Observatory. The continuous rainbow background was faint, and the broad, bright bands dominated the scene. Other discoveries followed, including a few stars bright enough to be seen without a telescope —such as Omicron[2] Canis Majoris, not far from Sirius. In the Pickering classification the bright-line objects were lumped together with other very hot stars and placed in Type O, but nowadays the true Wolf-Rayet stars have been placed in a new class, W.

All are luminous, thousands of times brighter than the Sun, and all are remote. What is really surprising, however, is their surface temperature. Values of 60,000 to 100,000 degrees seem probable, so that our Sun, with its 6000-degree photosphere, seems very mild

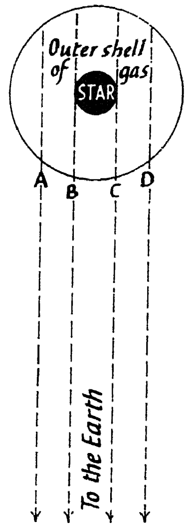


FIG. 22. Emission and absorption lines. This diagram (very much out of scale, for the sake of clarity) shows a star with a vast gaseous surround. As seen from Earth, absorption lines will be produced between B and C, since the situation is the same as for a normal star such as the Sun, but other parts of the 'shell', such as those in directions A and D, will produce emission lines —since they will be seen away from the 'background' of the star. This picture is dangerously over-simplified, but may suffice to give the general idea.

by comparison. The colour is, naturally, white, and the typical Wolf-Rayet star has a diameter of two or three million miles.

We know that an absorption line is produced by the effect of a hot gaseous layer seen against the background of the star's surface. The only way to explain the emission lines of W stars is therefore to suppose that much of the 'chromosphere' is *not* seen against such a background—so that the chromosphere must be of great extent. In such a case the situation will be much as shown in the diagram; the shaded area will yield absorption lines in the usual way, but the remainder of the chromosphere will produce emission lines.

Strictly speaking the term 'chromosphere' is rather misleading when applied to W stars, since the layer surrounding the bright surface seems to take the form of an expanding shell of gas, and differs considerably in nature from the solar chromosphere. It is also worth noting that many W stars are close binaries, the fainter component being usually an even more massive star of spectrum O.

The O stars themselves, as well as a few in Type B, show some emission lines, and these too indicate the presence of an extended shell of gas. In cases where we find a binary system, one being of class W and the other of O, it may be that there is a vast gaseous shell which includes both stars—truly a complicated arrangement, since it is possible that there may be a flow from the 'atmosphere' of one star to that of the other.

Before dealing further with shell stars, it is worth saying something about the rates at which the stars rotate, since this is bound up with the whole problem. The Sun takes rather less than a month to spin once on its axis, as may be judged from the rate at which spots appear to be carried across its surface; it takes a spot roughly a fortnight to pass from one limb to the other. Since we cannot observe spots on the stars, we have to return—as usual—to the spectroscope, and make use of what is known as the Doppler effect.

If you stand beside a railway track and listen to a whistling engine approaching you, the note of the whistle will be high-pitched. As soon as the train has passed by, and begins to recede, the note of the whistle will drop. There is a simple explanation for this. During approach, rather more sound-waves per second are entering your ear than would be the case for a stationary train; the 'wave-length' seems therefore to be shortened. During recession, fewer sound-waves per second reach you, so that the wavelength appears to be lengthened and the note of the whistle falls.

It is much the same with light. The wavelength seems to be less if the source of illumination is approaching, so that the light is slightly 'bluer' than would otherwise be the case. If the light-source is moving away, there is a corresponding reddening. The actual colour change is much too slight to be noticed, but there is an effect upon the positions of spectral lines, as shown in the diagram.

In figure (*a*), the position of some particular line is given on the assumption that the light-source is motionless relative to the observer. In (*b*) the source is approaching, and the line is displaced toward the short-wave or violet end of the spectrum; in (*c*) it is receding, and there is a red shift. The diagram is out of scale, since the actual displacements are so tiny that they cannot be detected without accurate measures, but the general principle is clear enough.

Now let us consider a rapidly-spinning star. Unless we are looking straight at the pole of rotation, one limb will be approaching us and will give a violet shift, while the other limb will be receding and will yield a red shift. The effect is easy to explain by means

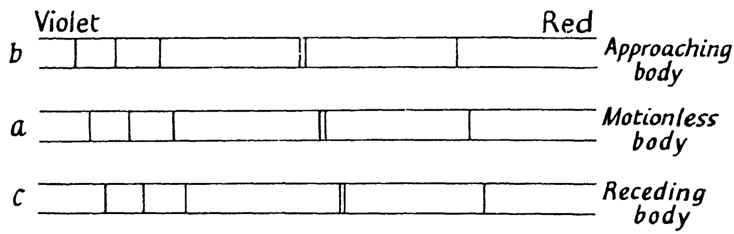


FIG. 23. Doppler shifts in spectrum lines. In the middle diagram, *a*, the light source is considered to be at rest to the observer. In *b*, the source is approaching, and all the spectrum lines are shifted to the violet or short-wave end of the spectrum. In *c*, the body is receding, and there is a red shift.

of a simple experiment. Take a tennis ball, and pencil in a spot and a cross separated by 180 degrees. If you now hold up the ball and spin it round, the spot will be approaching you while the cross recedes, and vice versa.

For our quickly-spinning star, then, the spectrum lines will be displaced both toward the violet and toward the red: in other words, they will be spread out and broadened. If we see exceptionally broad lines, we may be fairly sure that the star is in rapid rotation.

The Earth is spinning, and in consequence the equatorial zone bulges slightly, making the diameter as measured through the equator 26 miles greater than that measured through the poles. The planet Jupiter, which is much larger than our world, takes only 9¾ hours to complete one turn, and the distortion is greater; the equatorial diameter is 5000 miles more than the polar. But with some stars, the rotation is so rapid that the star itself is drawn out into a shape which is not even approximately spherical.

All shell stars are in quick rotation, and one of the most interesting, Pleione, may be taken as a good example. It is easy to identify, since it lies in the prominent cluster known as the Pleiades or Seven Sisters; it has a B-type spectrum, and is of the 5th magnitude, so that it is visible to the naked eye. The rotation is about 100 times faster than the Sun's, which is so rapid that in addition to the flattening there is a good chance that material will be flung off Pleione's equatorial zone, forming a sort of gaseous ring—in shape not too unlike the ring system surrounding the planet Saturn, though entirely different in character.

This may actually happen. One such outburst took place in 1938; we have some idea of the sequence of events, though of course the ring itself could not be seen. Some extra disturbance inside Pleione increased the acceleration of gaseous atoms outward from the star's photosphere, near the equator, and the formation of a temporary ring resulted. This lasted for some years, but finally no more material became available to maintain the ring, and by 1952 it had vanished. As a matter of fact Pleione had previously been known to behave in such a way, so that periodically it sprays material away into space.

Another interesting shell star is 48 Libræ, which lies not far from the 2nd magnitude star Delta Scorpionis. Here again the spectrum is of type B; the diameter is over 4 million miles, and the surface temperature 20,000 degrees. It is remote, since its distance amounts to nearly 650 light-years. (If you look at it tonight, you are seeing it not as it is, but as it used to be when Robert Bruce still lived.) 48 Libræ has been said to have two atmospheres. The inner one gives the usual broad lines indicative of quick rotation; the shell is largely in the form of a ring round the star's equator, and tapers into a cloud of tenuous gas which yields hydrogen lines of normal sharpness. Here too there are outbursts which cause marked changes in the spectrum.

Were the Sun a shell star, we would be presented with a magnificent spectacle. Instead of having to look for changes in bright and dark lines against a rainbow spectrum, we would be able to see the outbursts from close range; the rings would be clearly visible, and we would be able to watch the physical changes as they took place. On the other hand, can it be possible for a shell star to possess a planet family at all? This brings us to another important problem.

We have been dealing with the surfaces and immediate surroundings of the stars, but in the case of the Sun we also have to reckon with a family of planets, the most distant of which—Pluto—lies at a mean distance of well over 3000 million miles. Since the Sun is so unremarkable, and is in no way to be singled out from many other stars of similar kind, is it possible that such planet families exist elsewhere?

The question would be easier to answer if only we knew how the Earth itself came into being. Unfortunately we do not, and at the moment there are various theories, all of which have their strong and weak points. On one hypothesis, the Solar System originated as the result of the 'explosion' of a star which used to accompany the Sun as a binary companion; if this is so, planet families will be the exception rather than the rule, though in a galaxy of at least 100,000 million stars we may expect to find a good many of them. More generally favoured, however, are theories of the type proposed by scientists such as Schmidt of Russia and von Weizsäcker of Germany, who believe that the Sun once collected a cloud of dust and gas as it passed through interstellar material, so that the planets were gradually built up out of the material accumulated. Interstellar clouds are common enough, and so on this view planet-families are likely to be common too.

The trouble is that direct proof is impossible to obtain. A moment's reflection will show the reason for this. A planet, unlike a star, has no light of its own, and shines only by reflection. It is also very small judged by stellar standards, and even Jupiter, which we regard as colossal, has only 1/100 of the Sun's diameter. If we could take Jupiter and put it at the distance of even the nearest star, Proxima Centauri, it would be extremely hard to detect even with telescopes far larger than those available to us at present. The 200-inch Palomar reflector and the projected Russian 236-inch reflector would be hopelessly inadequate.

However, there is another method of investigation which has borne fruit in the case of our old friend 61 Cygni, the star which became famous as being the first to have its distance measured. As we know, 61 Cygni is a binary system; both components are K-type red dwarfs much smaller and fainter than the Sun, and it is the feebler of the two (61 Cygni B) which has proved to be so remarkably interesting.

As in all binary systems, the two components revolve round their common centre of gravity, in this case taking about 700 years to complete one revolution. In addition, B seems to be 'wobbling' very slowly and very slightly. There can be only one explanation: it is being pulled out of place by a third body, and at first it was assumed that the unknown component must be a very faint star, so that it was designated 61 Cygni C. Then, to astronomers' surprise, further facts came to light, and it was found that C has only about 15 times the mass of Jupiter. This is much too little for a star, and so the body may be a planet—a virtually non-luminous globe, dependent for its light and heat entirely upon the feeble sun around which it moves.

We have no idea of its physical condition, and probably we never will find out. It may be entirely different from any planet in the Sun's family, and there is always a chance that it retains a certain amount of inherent luminosity, but there seems little doubt that it is basically non-stellar in nature. It is not unique; in recent years a few other nearby stars have been found to be similarly accompanied.

All our knowledge is indirect, but the little we can tell leads us to suppose that planet-families are, after all, quite ordinary. This is only to be expected. There are 100,000 million stars in the Galaxy; the Palomar reflector can photograph 1000 million galaxies, most of them comparable with our own; and so it would be unwise to suppose that our particular Solar System is the only one. Our ignorance of how the planets were formed is of no real account here. The Sun must have been directly concerned in some way, and what can happen to the Sun can undoubtedly happen to other stars as well.

Of course, we have entered the realm of speculation, but it is interesting to consider the various 'suns' which might warm our hypothetical 'other Earths'. The parent might be a vast Red Giant such as Betelgeux, in which case any inhabited planet, at least, would have to lie well out; the parent might be a celestial searchlight of the Rigel type, or it might even be a binary, in which case a circling planet would be forced into a very complicated orbit. It would indeed be diverting to be provided with twin suns, one orange and one, say, bluish-green!

At least it is clear that we have found out something about the surfaces and surroundings of the stars. Perhaps some astronomer living in a far-away solar system has been working along the same lines of investigation—and perhaps at this very moment he is writing a book in which he suggests that a certain faint yellowish orb, the one we call the Sun, may be accompanied by a planet-family of its own.

8

The Life of a Star

What keeps the Sun shining?

This is a question which must have been asked even by the earliest men, who believed the Earth to be a flat plain lying in the centre of the universe. It is still being asked today, and during the last twenty-five years we have started to find out at least part of the answer. If we can solve the secret of the Sun's supply of energy, we ought to be able to tell what conditions are like deep down inside the stars, and this in turn will lead us on to a star's life-story.

We can measure the surface temperatures of the stars, and we know that these range from well over 50,000 degrees for Types W and O down to only about 3000 degrees for the cool late-type red stars. But even 50,000 degrees is not much when we consider the heat inside a star's globe; the rule is, 'the deeper, the hotter'. We can forget Herschel's amazing theory of a cool, habitable region below the solar photosphere, and it can be shown that the temperature near the middle of an average star is in the region of 20 million degrees.

Such heat is beyond the powers of human imagination—but no more so than the immense distances and time-spans which we meet in stellar astronomy. We have to admit, reluctantly, that our brains are too limited to understand what it all means.

The stars are emitting energy all the time, and this shows that they cannot last for ever. Eventually their sources of power must become exhausted, and the stars will 'die'. Neither will they keep radiating in the same manner from birth to extinction; they must evolve, and old stars behave differently from young stars. The trouble is that they change too slowly for us to have the slightest hope of catching them in the act.

There is a good everyday comparison here. Let us suppose that a visitor from Mars, who has no previous idea of what a human being looks like, pays a visit to Earth and walks down Oxford Street during the rush hour. He will see infants, youths and men; he will not be able to watch a schoolboy suddenly grow up, but if he has any reasoning power he will soon be able to fit the various examples of *homo sapiens* into the correct evolutionary sequence, beginning with the babies and ending up with the greybeards. From this, he will be able to work out how a human being develops.

We are faced with much the same sort of problem when we consider stellar evolution. There are young stars, middle-aged stars and old stars; once we can arrange them properly, we will be on the right track. Unfortunately it is by no means easy to tell which are the 'babies' and which are the 'patriarchs'. Fifty years ago, for instance, it was thought that the Red Giants such as Betelgeux were just starting their careers; now we hold the view that they are decidedly senile.

There is the further complication that not all stars go through identical stages. They have their individual peculiarities, and the 'oddities' sometimes tend to confuse the issue. Among these oddities are the W and O stars, the supergiants such as Betelgeux, and the particularly luminous stars such as Rigel, all of which are relatively rare.

Luckily we have one or two established facts which we can use as a foundation for our theories of stellar evolution. The firmest of all concerns the time-scale. We can show that the Earth is at least 3000 million years old; the Sun, which must have been concerned in the formation of its planet-family, is certainly older than this—and so we have a lower limit for the Sun's age. Incidentally, we can make use of another condensed scale to show how tremendous this period is. Suppose that we begin by reducing the whole civilized era into a single second of time, so that on our scale the Battle of Hastings, the founding of Rome, the siege of Troy and the building of the Pyramids all took place less than a second ago? We can then put in other events in the history of our world. The first primates, the tree-dwellers from which are descended monkeys, apes and men, flourished '1¼ hours' ago; the first mammals go back '5½ hours', and the first definite proof of life anywhere on Earth takes us back '14 hours'. Before that time there is no evidence of any living creatures, but the oldest rocks came into being '47 hours' ago, while the Earth itself was formed between 80 and 85 hours ago on our scale. The last figure, of course, stands for some 3000 million years on the real scale.

To sum up: if we represent the age of the Earth as about 3½ days, the whole story of civilization, from the first townships up to the present enlightened age of nuclear bombs and poison gas, occupies only one second. A conservative guess makes the Sun at least twice as old as the Earth, which takes us back for one week on our compressed scale.

Other facts which we know with fair accuracy are the mass of the Sun; the temperature of the solar surface; and the rate at which energy is being poured out. And in consequence we can at once reject the idea that the Sun is burning in the same manner as a coal fire. Lord Kelvin, in the nineteenth century, showed that in such a case the Sun would burn completely away in a few thousands of years, and could not possibly have existed for the 3000 million years since the formation of the Earth. If this is true for the Sun, it is certainly true for other suns as well.

It seems that a star begins its career by condensing out of an interstellar dust-and-gas cloud. We know of many such clouds, and term them galactic nebulæ, of which the best known lies in the Sword of Orion. These nebulæ may be regarded as the birth-places of the stars.

The material making up such a cloud is incredibly tenuous—millions of times less dense than the air we breathe—but it cannot be perfectly uniform throughout its mass. There must be places where the material is slightly denser than usual, and this will result in a local condensation. As soon as the condensation becomes marked, gravitational forces will come into play. Each particle will tend to attract its neighbours, and the result will be that the material will start to bunch together toward the middle of the condensation, as well as drawing in fresh particles from neighbouring regions.

So far we have a cloud of material collecting in a definite zone in the nebula, but it is not yet a star, since it is emitting no radiation. Indeed, the whole contraction process may last for a million years at least. For a long time there will be nothing to stop the steady shrinkage, and all the while the material will become denser near the middle, resulting in a rise in temperature. At last there comes a period when the central region becomes so hot that radiation begins; this calls a halt to the contraction, at least for the moment, and the body starts to shine. A star has been born.

The Orion nebula is only one of many such interstellar clouds, but it happens to be unusually close to us on the cosmical scale, and so we can study it in some detail. It is thought that some non-luminous patches may represent embryo stars which have not yet started to radiate; it is also believed that some curious dwarf variable stars, discovered inside the nebula by Miss Henrietta Leavitt more than forty years ago, may be true stellar infants which have only just been created out of the nebular material. Whether this be true or not, the dwarf variables are extraordinary objects. Their brightness changes quite irregularly, their spectra show both absorption and emission lines, and their luminosities are comparable with that of the Sun.

So far we are on firm ground, but we still have not explained why a star emits radiation at all. Originally it was thought that the heat generated by gravitational contraction might be enough to last the star all through its career, and this led Sir Norman Lockyer, a leading British astronomer of the late nineteenth century, to put forward a definite theory of evolution which sounded delightfully straightforward. Actually Lockyer was wrong; nevertheless, his work laid the way for a better understanding of the stars.

Lockyer began by describing the process by which a star condenses out of a nebula. He pointed out that the original temperature would be low, and the still-contracting star would be large, so that its surface would be cool and red; Betelgeux and Antares would be good examples. As the contraction went on, the temperature would continue to rise; the star would become successively an orange giant (Arcturus), a yellow giant (Capella) and then a much smaller, very luminous white body such as Rigel. This would be the peak of the star's career. The gravitational contraction would continue, but the temperature would drop as well, and the star would pass steadily down what is termed the Main Sequence to become a less energetic white star (Sirius type), then a yellow dwarf (the Sun) and finally a red dwarf (Proxima Centauri). In its extreme old age all heat would leave it, and it would turn into a cold, dark globe.

Lockyer's theory accounted excellently for the fact that the orange and red stars are divided into giant and dwarf groups, while the hotter stars are not. The remarkable thing here is that when Lockyer put forward his ideas, the giant and dwarf divisions had not been recognized. In consequence, the recognition of the giant and dwarf groups some years later was held to be a significant confirmation of all that Lockyer had said.

But though the sequence seemed to be logical, it was already clear that Lockyer's suggested energy source—pure gravitational contraction—was not. A star which radiated only because of this could not possibly last for more than 50 million years, and yet the Sun was known to be more than 3000 million years old. Something was badly wrong.

Henry Norris Russell, famous for his work in connection with giant and dwarf stars, put forward a better idea. He retained Lockyer's evolutionary sequence, making the Red Giants very young and the Red Dwarfs very old, but he introduced power from the atom, and supposed that a star shone because it was steadily converting its matter into radiation.

Nowadays it is seldom that a day passes without some official reference to atomic power, but how many people have any real idea of what an atom is like? We know that there are only 92 naturally-occurring types, the 'elements', and that each type has its own characteristics leading to the production of its own particular spectral lines; but if we are to find out how the stars radiate, we must turn to physics and say something about the structure of the atom itself.

The trouble here is that it is impossible to give an accurate picture without using mathematical language. Plain English simply will not do. There is a homely analogy; how can one explain a musical note to a man who is completely deaf and always has been? You cannot write down a tune. You can, of course, produce a conventional representation, and here, as an example, are the first few notes of 'God Save the Queen':

Yet this would mean absolutely nothing to a person who has never heard a musical note. Our language is completely inadequate.

It is the same with the atom. Fifty years ago scientists had produced an excellent picture of it, but unfortunately the picture is not one which can be taken literally. All we can do, however, is to describe it first and deal with its shortcomings afterwards.

We begin with the atom of hydrogen, which is the simplest of all. It is made up of two components: a central nucleus, consisting of a particle called a proton, and a much less massive particle termed an electron, which revolves round the nucleus just as a planet revolves round the Sun. The proton carries a unit charge of positive electricity, while the electron carries an equal charge of negative electricity. In consequence the two electrical charges cancel each other, and the atom as a whole is electrically neutral. (It does not take any great mathematical skill to see that $+1-1 = 0$!)

Helium, the next lightest element, is more complex. There are two planetary electrons, and since we must keep the whole atom electrically neutral we must give the nucleus a double positive charge—so that instead of being a single proton, it becomes a compound structure, perhaps made up of two protons.

We can continue up the scale, adding an extra electron for each element and at the same time introducing an extra charge into the nucleus. Oxygen, for instance, has 16 planetary electrons. Finally we reach uranium, which has 92 planetary electrons and a very complex nucleus. (Still heavier elements have been produced in our laboratories, but we have no proof that they occur naturally.)

It is now clear why we can be so sure that we know all the elements. There is no room for an extra one in our series; you cannot have half an electron, since an electron is indivisible, and so it is clearly out of the question to put a new element between, say, helium (two planetary electrons) and lithium (three).

The picture is rather like that of a miniature Solar System, with the atomic nucleus taking the place of the Sun. Moreover the atom, like the Solar System, is mostly empty space; the nucleus and the electrons are tiny in comparison with the total room which the atom occupies.

To complete our picture, let us see what will happen if an atom meets with an accident and loses an electron. If we knock off one circling electron from a lithium atom, we will be left with a nucleus and two electrons—but this will not be the same as a helium atom, because the lithium nucleus can balance the electrical charge of *three* electrons. The result will be an incomplete lithium atom with an overall positive charge. An atom which has lost an electron in this way is said to be ionized, and the process can be continued until all the planetary electrons have been stripped away, when the ionization is complete.

It all sounds very easy, but unfortunately we now know that it is misleading to think of an atom in precisely this way. We are entitled to keep the concept of a central nucleus and circling electrons, so that the Solar System analogy is retained; what we must not do is to think of either nucleus or electrons as solid lumps of matter. Neither must we imagine that their movements are the same as those of planets. The whole situation is much more complicated, and it is at this point that ordinary English fails us.

Fortunately we need not go any further at the moment. Our idea of the atom as a Solar System, with electrons revolving round a nucleus, is good enough for our present purpose—so long as we are careful not to take it literally. Now we can go back to Russell's idea of how a star produces energy.

A proton carries a positive charge of electricity; an electron carries an equal negative charge. Suppose that the two meet, and cancel each other out? One minus one still equals nought, and Russell considered that the result would be the complete disappearance of both particles, with the production of energy. Eventually the whole star might be transformed into radiation, and this time there would be no fear of complications due to the Sun's age. So much energy would be available that the lifetime of a star would amount not to 50 million years, but to something like 10 million million years.

Russell's annihilation of matter theory, in its various forms, held the stage for two decades after its first publication in 1913. It all seemed highly plausible. A star would begin as a Red Giant, pass down the giant branch until joining the Main Sequence at type O, B, or A, and would then move down the Main Sequence itself, losing mass as it annihilated its material until its energy was spent. There was plenty of power to spare, and the famous chart known as the Hertzsprung-Russell Diagram showed a true evolutionary track from birth to near-death.

Then, gradually, new facts came to light, and astronomers were forced to look suspiciously at the whole theory. It became painfully evident that whereas Lockyer's time-scale had been much too short, Russell's was far too extended. Ten million million years was much too long a period; what was needed was a happy mean. Moreover, increased knowledge of atomic structure cast discredit upon the straightforward mutual annihilation of a positive particle and a negative one. The process did not work, and nothing would make it work. By the early 1930's the whole question was open once more, and no theory gained general acceptance—so that one famous authority said wryly that he knew all about stellar evolution in 1915, rather less in 1920, and nothing at all since 1929.

This was the situation shortly before the war, but then a sudden inspiration on the part of Dr. Hans Bethe, a German scientist working in America, opened a new avenue. Apparently Bethe was journeying by train from Washington, where he had been attending a conference, back to Cornell University when he decided to pass the time by calculating some nuclear reactions capable of accounting for the observed energy output of the Sun. Almost at once he obtained a most convincing solution. We know now that he was not entirely correct, inasmuch as his process is not the main one which produces solar radiation; but it is operative for many stars, and modern theories are founded largely upon the Bethe formula. All in all, that particular train journey was a most important one, though it should be added that a rather similar answer was given by Carl von Weizsäcker, in Germany, about the same time. The key to the whole problem is hydrogen.

Hydrogen is by far the most plentiful substance in the universe, and it is in fact more abundant than all the other elements put together. The Sun, like most other stars, contains a tremendous amount of it. Near the Sun's centre, where the temperature is about 20 million degrees and the pressure is colossal, conditions are suitable for strange things to happen to the hydrogen nuclei; they band together, and change into helium nuclei. It takes four hydrogen nuclei to make one nucleus of helium, but Bethe saw that there must be more to it than a simple running-together, and worked out that carbon and nitrogen, two elements very familiar to us, might be used as 'catalysts'—that is to say substances used during the series of transformations, but which themselves emerged unaltered. The net result, then, could be summed up as the steady building-up of helium out of hydrogen.

The essence of the whole theory is that the helium-building process releases energy. Moreover, the single helium nucleus produced has a mass slightly less than that of the four hydrogen nuclei which went into it, so that mass has been lost. This is not the same thing as Russell's old idea of the direct annihilation of matter, but it gives rather the same result on a modified scale. Each time a helium nucleus is built, the Sun loses a little mass, and energy is released. It is this energy which keeps the Sun shining.

The carbon-nitrogen cycle is only one of several ways in which helium may be produced from hydrogen, and it is another, the so-called 'proton-proton' reaction, which has proved to be the most important in the case of the Sun. However, the final results are just the same; four hydrogen nuclei produce one helium nucleus plus energy.

An atom is inconceivably small, and it is not easy to understand how such a process can keep the Sun radiating for year after year, decade after decade, century after century. The answer lies in the Sun's tremendous mass; there is so much hydrogen that a great deal of energy is being set free all the time. Each second, the Sun loses mass to the extent of 4 million tons, so that if it has taken you a quarter of an hour to read this chapter the Sun now has a mass of 3,600 million tons less than was the case when you picked up the book.

This may seem a staggering loss—and indeed it is; but it fits well into the time-scale. We are neither too long nor too short. The Sun has so much material that it can well afford to lose it at such a rate, and there is enough 'fuel' to last it for thousands of millions of years yet.

This does not apply to more energetic stars. Rigel, for instance, is exceptionally luminous, and is squandering its nuclear fuel at an amazing rate. The mass loss must be well over 80,000 million tons per second, as against the comparatively placid Sun's 4 million.

Even Rigel cannot stand this loss for long on the cosmical scale, and neither can it have existed in its present state for nearly so long as the Sun. It cannot have shone with its modern brilliance for many millions of years, and it will age relatively quickly.

Rigel, with its luminosity of 18,000 Sun-power,* is by no means the supreme searchlight of the heavens. S Doradûs, unfortunately too far south to be visible in Britain, has a candlepower almost one million times that of the Sun, and yet is so remote that without a telescope we cannot see it at all. S Doradûs is a real spendthrift, and it cannot have kept up this fantastic output for as much as a quarter of a million years. Other stars known to us are even more luminous.

It is tempting to cling to the old Lockyer sequence of evolution, making the Red Giants young, the white O and B stars middle-aged, and the dwarfs old. On this scheme stars such as Rigel would gradually cool down into calmer bodies of the same type as the Sun, while the Sun itself would dwindle into graceful old age as a Red Dwarf. As usual in astronomy, things are not so clear-cut as this, and by now we have no choice but to abandon the Lockyer sequence completely, in spite of its plausibility. It is time to take a fresh look at stellar evolution, and see where modern theories lead us.

We start off from the same point: the condensation of a star out of nebular material. The centre heats up, and radiation begins, but how long the initial contraction goes on depends upon the mass of our embryo star. For the Sun, a possible figure is 30 million years; a more massive star will go through the process more quickly, while a less massive body will take longer. However, the inevitable result is that nuclear processes begin, with the conversion of hydrogen into helium. The star has reached the Main Sequence; it has stopped its rapid shrinking, and has begun the adult phase in its life-story.

It will be seen, then, that the Main Sequence stage comes before the Red Giant stage (even on the assumption that all stars become Red Giants at some time or another). This gives a definite *coup de*

* This is not a precise figure, and some recent estimates make Rigel more luminous still. It is so remote that a reliable value is hard to obtain, and this applies also to other very distant and powerful stars such as Canopus.

grâce to the Lockyer evolutionary march from Red Giant down to Red Dwarf.

The energy of Main Sequence stars such as the Sun is derived almost exclusively from the conversion of hydrogen into helium. The carbon-nitrogen cycle seems to be more important in the hotter stars, and the proton-proton reaction in cooler ones, but the end result is the same. The steady mass loss is tremendous, but not really significant when balanced against the total mass of the star; the Sun, for instance, has lost much less than 1 per cent. of its mass since the end of the last Ice Age.

The hydrogen in the central 'power-house' is being used up all the time, and helium, which under such conditions is inert, takes its place. Here we must probably draw a distinction between stars which are rotating rapidly, and those which are not. In the quick-spinners, of early spectral type, the materials throughout the globe will be thoroughly mixed; at different times all the hydrogen atoms will find their way to the central power-house, and will be available for helium-building. For stars which rotate more slowly, such as the Sun, the mixing will be less complete. A core of inert helium might be produced, and the generation of power might be transferred to a relatively thin layer around the core.

Probably the speed of rotation has a great effect upon what happens to a star at the critical period when all its available hydrogen fuel has been used up, so that it has to leave the Main Sequence. We must, however, decide whether hydrogen is the only fuel available, or whether other elements can be used in a similar way. For instance, is it possible to use helium to build up nuclei of the third element, lithium?—and can oxygen nuclei be used to produce heavier substances such as uranium?

Here we are rather unsure of ourselves. With greater temperatures it is at least possible that such reactions can occur, but the processes which may be going on inside very hot stars are still not known with any certainty. At least we can be definite in saying that stars such as the Sun are hydrogen-consumers first and foremost.

Now let us see what happens to a star which has used up all the hydrogen in its power-house, so that it is left with an inner core of completely inert helium. There is nothing to stop this core from shrinking once more under the influence of gravitation, and it duly does so, but when it has reached the stage of having about one-tenth of its mass contained in the inert core the whole star begins to rearrange its material in a drastic manner. Its outer layers expand tremendously, cooling as they do so, until the structure has changed completely. There is a relatively small, very hot, very dense core enveloped by a huge rarefied 'atmosphere'. In other words, our star has become a Red Giant.

Betelgeux is one such body; others are Antares and Mira. An even better example, however, is Rasalgethi, or Alpha Herculis. Rasalgethi is not spectacular to the naked eye, since it is below the 3rd magnitude, but it is easy enough to find when you know where to look for it. It yields an M5 spectrum, and has a surface temperature of only 2700 degrees, but its diameter has been estimated at 250 million miles, which is greater than that of the Earth's orbit round the Sun. Even this may be a marked under-estimate, and Rasalgethi certainly earns its title of 'giant'. On the old theories, it and Betelgeux were mere infants, but now we believe them to be more advanced in their careers than the Sun.

Not all astronomers agree with this model of a Red Giant. On another theory there is no small, dense core, in which case the central temperature must be lower than for Main Sequence stars. Neither is there any definite agreement upon the energy-sources of the Red Giants, though many suggestions have been made.

The giant stage cannot last for ever, and once the star has exhausted all its nuclear power it must alter its structure yet again. The exact course of events is not well established, but it looks as though the most senile stars known to us are the very faint, incredibly dense bodies known as White Dwarfs. These stars are of very small size, and their luminosity is feeble. It is often held that a White Dwarf is made up chiefly of helium, and that it continues to shine feebly only because of gravitational shrinkage.

It is important to remember that even though we use the term 'White Dwarf', the white stars are not split into giant and dwarf groups in the same way as the red. A White Dwarf is built upon an entirely different pattern, and has been aptly described as a bankrupt star, without any fuel resources whatsoever. It can evolve no more, and all it can do is to go on radiating dimly until the last of its energy leaves it. No White Dwarfs are visible to the naked eye, even though some of them are very near us on the astronomical scale; they are the glow-worms of the Galaxy.

The discovery that normal stars radiate because of nuclear reactions going on inside them has caused a complete somersault in our ideas. Instead of becoming feebler as it ages, as used to be supposed, the Sun is growing more luminous. Of course its changes are so slow that no alteration will be detectable in our time, and a million years hence the Sun will look much the same as it does now. Yet when its hydrogen fuel is exhausted, there is a possibility that its outer layers will swell, and there is a chance that the Sun will turn into a Red Giant, even though it will hardly match Betelgeux or Rasalgethi.

Despite the lower surface temperature, the Sun will then be giving out much more total energy than it does today, and the effects on our own world will be disturbing—to say the least of it. The heat will become so great that the oceans will boil, the atmosphere will be largely stripped away, and life as we know it must come to an end. Subsequently the Sun may become a White Dwarf, so that if the Earth still exists it will be plunged into the bitterest cold. It is thought that the crisis will come between 5 and 10 thousand million years from now, probably nearer the latter figure.

We cannot hope to see so far ahead; we have no idea what conditions will be like in the remote future, and in any case there is always a chance that our present theories of stellar evolution are hopelessly wide of the mark. Yet it is as well to remember that even though the stars are long-lived, they are not eternal. Nothing in the universe lasts for ever, and there must come a time when our world will exist only as a scorched-up, airless globe circling lifelessly round its dying Sun.

9

Double Stars

In the year 1650 Father Riccioli, a Jesuit priest who was interested in astronomy and became famous for drawing a reasonably good map of the Moon, made an interesting discovery. On turning his telescope toward Mizar or Zeta Ursæ Majoris, the second star in the handle of the Plough, he saw that it was double. Of course, the nearby star Alcor had been known for centuries—the pair used to be called 'Jack and his Wagon'—but Riccioli found that Mizar itself was made up of two stars, so close together that to the unaided eye they appeared as one.

Riccioli did not know that the two components of Mizar were really associated. It was not until Sir William Herschel made his investigations, more than a century after Riccioli's time, that the true nature of physically connected or 'binary' stars became clear. However, telescopes revealed more and more doubles, and astronomers had to realize that stellar pairs were remarkably common.

The apparent separation of the components of a double star is measured in seconds of arc. Alcor is about 700 seconds of arc from Mizar, which is rather too far for it to be classed as a 'double' in the accepted sense of the word, whereas the stars of the close Mizar pair are separated by 15 seconds of arc—wide enough for the pair to be split with even a small telescope, and yet not a great deal when we remember that the apparent diameter of the Moon is roughly 1800 seconds of arc.

The 'position angle' of a double star, binary or otherwise, is the apparent direction of the fainter component (B) as reckoned from the brighter (A), beginning with 0 degrees at the north point and measuring round by east, south and west back to north. Binary stars with short revolution periods have distances and position angles which change quite rapidly, so that it is never safe to trust the values given in books or catalogues more than a few years old. There is no such change for the optical doubles, or for binaries whose components are at a tremendous real distance from each other.

Before going into more details about binary-star astronomy, it will be worth while to spend a few moments in describing a few of the most conspicuous pairs. The interest of a binary system is always enhanced as soon as you have found it for yourself, and know what it looks like; the practical observer has a tremendous advantage over the man who is content to study from the depths of an armchair.

We may make a start even if no telescope is available, since in addition to the Mizar-Alcor pair there are several doubles separable with the unaided eye. For instance, Theta Tauri, in the Hyades star-cluster close to Aldebaran, is an easy object, and its position makes it readily identifiable. In summer evenings, when the Hyades are below the horizon in Britain, we have another naked-eye double: Epsilon Lyræ, very near the brilliant Vega. And in autumn we may turn to the rather inconspicuous constellation of Capricornus, the Sea-Goat, whose main claim to fame is that it lies in the Zodiac. Both Alpha and Beta Capricorni are wide doubles; Alpha or Al Giedi, with a separation of 376 seconds of arc, needs no telescope at all, and is convenient enough to lie in line with the trio of stars in Aquila of which Altair is the leading member. Beta Capricorni has stars of magnitudes 3¼ and 6 separated by 205 seconds of arc, so that binoculars will deal adequately with it.

A small instrument provides enormous scope. Quite the loveliest double of all is Albireo or Beta Cygni, the faintest star of the 'cross' of the Swan. It is of the 3rd magnitude, and is easy to find, as it lies roughly between Vega and Altair. The yellow primary is accompanied by a 5th magnitude companion which is of a strongly greenish hue,* and the effect is beautiful. The colours are vivid, though the greenness of the companion is accentuated by contrast with its yellow leader.

Very different is Theta Serpentis, which lies not far from Altair. Here we have two stars, each of magnitude 4½, and which seem to be perfect twins, alike in every way. With Gamma Virginis, in the 'Y' of the Virgin between Spica and Regulus, one component is

* Some people prefer to call the companion blue or blue-green. It depends on one's eyes.

only very slightly brighter than the other; the revolution period is about 180 years, so that the distance and position angle change appreciably over the course of a lifetime. The separation was at its widest (just over 6 seconds of arc) in 1920, and is now closing, until by the year 2016 Gamma Virginis will appear single except in very large telescopes. Another case of virtual twinning is Gamma Arietis, in the Ram not far from the Square of Pegasus, while there is a difference of about a magnitude between the two senior components of the famous Castor in Gemini.

Southern observers have two magnificent binaries in Alpha Centauri, the closest of the bright stars, and Acrux, the leader of the Southern Cross. A small telescope will separate both these.

With other doubles, one component is very much brighter than the other. A good example is Rigel in Orion, which has a companion of below the 6th magnitude; a small telescope will show it, though the faint star is naturally very much overpowered by the brilliance of the primary. The Pole Star is similarly attended, but the companion is dimmer—about magnitude 9—and at least a 3-inch telescope is needed to show it properly. Antares in Scorpio and Rasalgethi in Hercules, both vast M-type supergiants, are seen to possess greenish companions; with Izar in Boötes, near Arcturus, the primary is yellowish and the companion blue.

These are just a few of the many double stars in the heavens. The full list runs into many thousands, and to make a complete check of all the pairs available to even a modest telescope would need a great deal of work. Incidentally, there is scope here for the serious observer with slightly more complex equipment; by the use of a measuring device known as a micrometer, attached to a telescope such as a 6-inch refractor, he can make himself very useful in measuring the position angles and separation distances of binary pairs. Many of the published values are completely out of date—yet they keep on appearing in star catalogues, textbooks and yearly almanacs. It is time that they were revised.

Optical doubles are of no special interest, but binaries are important in many ways. In particular, their movements give us a reliable clue to their masses. If we know the parallax of a binary, and also the orbits described by the two components, we can work out the combined mass of the system compared with that of the

Sun; and if we can measure the orbit of either component around the common centre of gravity or 'balancing point' of the system, as is sometimes possible, we can find the individual masses of the two stars as well. For instance, all the necessary information is to hand in the case of the splendid binary Zeta Herculis, where the magnitudes are 3 and 6½, and the period is 34 years. We can tell that the primary is slightly more massive than the Sun, while the companion has about half the solar mass.

This may not sound particularly important, but actually it is of vital significance. It is hard to obtain a direct measure of the mass of a single star, and in fact we cannot do so; we have to depend upon theory, and the binaries have given us foundations upon which to work. Incidentally, the most massive star known to us is a binary, known as Plaskett's Star in honour of the astronomer who first drew attention to it. The components are about equal, and each seems to have a mass some 90 times greater than that of the Sun. Such heavyweights are freakish in the stellar heavens; even the huge, rarefied Betelgeux is probably not more than 15 times as massive as the Sun. Unfortunately Plaskett's Star is very remote, so that it is a faint object.

The lesson of all this is that evidently the laws of gravity apply just as rigidly in distant star-systems as they do on Earth. Moreover, we have an example of the same problem very much nearer home. To measure the mass of a planet, we have to work out the effects which it produces upon other bodies. Up to 1877 Mars, which is a small world, was believed to be moonless, and its mass was not easy to find, since its relatively feeble pull upon other planets such as the Earth and Venus was barely detectable. Then Asaph Hall, in Washington, found two tiny satellites which whirl round Mars at distances of only a few thousands of miles. As soon as the orbits of these moonlets had been worked out, which took only a few days, the pull of Mars could be fixed much more accurately, and so the mass of Mars itself could be determined. In the same way, we can find the mass of a star much more easily if there is another star nearby upon which its gravitational effects may be measured.

When we look at the spectral types of binary stars, we find some interesting laws—though the cause of them is still uncertain. For almost identical twins, such as Gamma Virginis, the spectra are nearly always similar. When there is a marked difference in brightness between the components, the spectra too are different. If both stars belong to the Main Sequence, the companion is of later type than the primary; if the primary is a giant, the companion is either a giant of earlier spectral type, or else a dwarf of similar class.*

The reason for this state of affairs must be linked with the way in which binary systems came into being. It used to be thought that a binary must be the result of the break-up of a single star which had been rotating very rapidly, but nowadays it is more generally believed that the two stars of a binary were formed close together in the heavens, so that they have never been able to break free from each other's influence.

So far we have been talking about binaries in which both components are conspicuous in small or moderate telescopes. This is not, however, the case with one of the most remarkable binaries in the sky—Sirius, the Dog-Star.

Sirius shines so brilliantly that it is not easy for us to realize that it is by no means a supergiant. True, it is 26 times more luminous than the Sun, but it owes its great apparent brightness to the fact that it is less than 9 light-years away, so that of the 1st magnitude stars only Alpha Centauri is closer. Naturally, Sirius has an unusually large proper motion, and this was why Edmond Halley was able to show that it had moved perceptibly across the sky since the days when Hipparchus and Ptolemy had drawn up their star-catalogues.

In the ordinary way, a star with large proper motion travels across the sky in a uniform manner, but in 1834 Bessel—later to achieve extra fame as being the first man to measure the distance of a star—realized that Sirius was behaving oddly. Its motion seemed to be erratic, so that instead of travelling in a regular line it was 'waving' its way along. Each 'wave' was very tiny, and took about 50 years to complete, but the effect was certainly there.

No single star could possibly act in such a fashion, and Bessel therefore suggested that Sirius must have a binary companion, too faint to be seen and yet massive enough to pull on the bright star

* Though the sequence O, B, A . . . M is no longer thought to be evolutionary, we still term the hot stars 'early' and the red ones 'late' in spectral type. For instance, Arcturus (type K) is said to be of later type than Sirius (type A).

and account for the 'waving' motion. Bessel came to this conclusion not long before his death, in 1844, which is interesting because research of rather the same kind was going on in connection with our own Solar System. The planet Uranus, discovered by Herschel in 1781, had been behaving strangely; two mathematicians, Adams in England and Le Verrier in France, had decided that it must be affected by an unknown planet, and by studying the amounts by

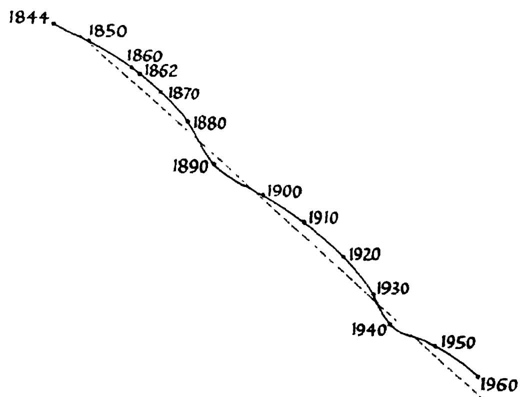


FIG. 24. The proper motion of Sirius. Because Sirius is being affected by the pull of its White Dwarf companion, Sirius B ('the Pup'), the path of the brilliant star is not a straight line. The motion is wavy, as shown here. Bessel explained this theoretically in 1844, and Clark first saw the Companion in 1862. Of course, the proper motion of Sirius is very slight judged by ordinary standards, and each 'wave' is so minute that sensitive instruments are needed to measure it. In the diagram, the dashed line represents the proper motion of the centre of mass of the Sirius system, and the continuous line represents the motion of the brilliant star (Sirius A).

which Uranus was pulled out of its calculated position they managed to track down the disturbing body—the planet which we now call Neptune. The crux of the matter was that Neptune's position was worked out before the astronomers actually started looking for it with their telescopes. In the same way, the position of the binary companion to Sirius was calculated, but the faint star obstinately refused to show itself.

In 1862 Clark, a well-known American telescope-maker, was testing a new refractor with a 20-inch object-glass. He turned it toward Sirius, and saw a dim dot of light close beside the brilliant star. This dot was, of course, the long-awaited Companion—just in the position which Bessel had predicted. It is known officially as Sirius B, and unofficially as the Pup, simply because Sirius itself is the Dog-Star.

The Pup is of magnitude 8½, which means that if seen on its own it would be an easy object in a small telescope. However, it is so overpowered by the light of the primary that it is not at all easy to glimpse. The position angle and separation alter fairly quickly, as the period is only 50 years; the distance will be at its greatest (11·5 seconds of arc) in 1975. It is said that the Companion may be glimpsed with a 6-inch telescope, but I have certainly never seen it with my own 12½-inch reflector, because observing conditions in Britain are seldom first-class and moreover Sirius does not rise high above the horizon.

When Clark made his discovery, the 'Sirius riddle' was regarded as closed. The Companion had been expected, and it had been duly found, which was most satisfactory. It was 10 magnitudes fainter than the primary, or approximately 10,000 times less luminous; in other words it had about 1/360 of the candle-power of the Sun. It was assumed to be a cool, red star of late spectral type.

Then, in 1915, W. S. Adams, of the Mount Wilson Observatory in California, produced an astronomical bombshell. He was able to study the spectrum of the Companion, and to say that the results were unexpected would be to put it mildly. Instead of being cool and red, the Pup turned out to have a curious spectrum corresponding to a white star—and the surface temperature was 8000 degrees, as against the modest 6000 degrees of the Sun. The supposedly dim red object had revealed itself as extremely hot and extremely white.

Astronomers were faced with a set of facts which seemed to add up to pure nonsense. The mass of the Pup, as shown from its effects on Sirius itself, was very nearly equal to the Sun's. The luminosity was only 1/360 of that of the Sun. The temperature measurement showed that each square inch of the surface was radiating roughly 3¾ times more light and heat energy than a square inch of the solar surface. Therefore, the surface area of the Sun had to be 360 × 3¾ times that of the Pup—which led to the conclusion that the Pup's diameter must be only about 24,000 miles, a mere three times as great as that of the Earth and much smaller than that of a large planet such as Jupiter, Saturn or Uranus.

Now let us check the density of the Pup material. What we have to do is to pack the mass of the Sun into a globe 24,000 miles across (remembering that the Sun itself has a diameter of 864,000 miles). The only way to do so is to make the material very dense, and the value calculated works out at 70,000 times the density of water, so that if you could take a matchbox and fill it with matter of this kind, the total weight would be more than a ton. Near the centre of the star, the density would be greater still, and you could pack perhaps 50 tons into a matchbox.

It is hardly surprising that at first, astronomers refused to accept any such value. It seemed quite incredible, and the easy way out was to suppose that some mistake had been made. Yet the facts could not be denied. The Pup was certainly faint, and it was certainly hot, so the only solution was to give it an extremely small diameter. Gradually, the puzzled scientists came to the conclusion that 'super-dense' material must exist after all.

Had the Pup proved to be the only object of its kind, it would have presented even more of a problem, but before long it became clear that similar 'White Dwarfs' were relatively common. Procyon has a White Dwarf companion; one of the two components of the binary Omicron^2 Eridani is a normally faint red star and the other a White Dwarf, and so on. Single White Dwarfs were also found, some of them much more remarkable even than the Pup. G. P. Kuiper has described one, known officially as A.C. +70° 8247 but more generally as Kuiper's Star, in which the diameter is about 4000 miles—roughly equal to that of the planet Mars—and yet the mass is the same as the Sun's. The material is incredibly heavy, so that if we could take a cube of it with each side of the cube measuring 1/10 of an inch, and bring it to Earth, the weight would be about half a ton. If however we could measure it on the surface of the star, the weight would be over 2 million tons—since the surface gravity on Kuiper's Star is about 3½ million times that on Earth!

If I personally could go to this strange world, I would find my weight increased to 50 million tons or so. Incidentally, the star's atmosphere is probably less than 20 feet thick.

Even Kuiper's Star may not be the extreme example. It has been suggested that a White Dwarf investigated by Luyten and Carpenter in 1952 may have a density some 85 million times that of water. However, values of this sort are bound to be uncertain, and stars of such type show no spectral lines at all—all that they present is a continuous rainbow.

There now seems no doubt that a White Dwarf is a 'bankrupt' star. It has used up all its nuclear power, and is radiating simply because it is still shrinking under the effects of gravity. Its atoms are very thoroughly broken up or ionized, and the material is made up of shattered pieces of atoms packed closely together with virtually no wasted space at all. Material of this sort is termed 'degenerate', and we can see how it accounts for the very high density. If you took the Sun and planets individually and forced them close together, you would take up far less room than the Solar System actually does, since the orbit of the outermost planet Pluto has a radius of over 7000 million miles; the proportion of wasted room in the Solar System is about the same as for an ordinary atom, but in a White Dwarf the pieces are tightly crammed.*

Apparently a star shrinks into a White Dwarf when its nuclear energy is finally exhausted, and there is no more available hydrogen or any other material which can be used as fuel. There is a chance that some White Dwarfs may consist chiefly of helium. The Sun may become a White Dwarf one day, after its period of glory as a giant, and it could then look foward to a placid old age, since these bankrupt stars radiate so very feebly that they can remain sensibly unchanged for immense periods of time. When even gravitational contraction can do no more for them, they must lose their remaining light and heat, ending up as cold, dead globes.

We have wandered some way from the main theme of this chapter. Since the White Dwarf class first became known because of the binary system of Sirius, a digression has perhaps been permissible, but it is time to return to our pairs of stars.

If the two components of a binary are extremely close together,

* This is a reasonable analogy, but remember the danger of regarding the particles of an atom as solid lumps—a picture which is convenient but misleading.

no telescope will split them. Here, as usual in stellar astronomy, we can make use of the spectroscope, which allows us to investigate binary systems which appear telescopically as single points of light.

Suppose that we are dealing with two stars, very near together and of much the same luminosity. In this case the period of revolution will presumably be short; less than a month, since if the period were greater the separation also would be greater, and we would have an ordinary visual pair. If the orbital plane is more or less

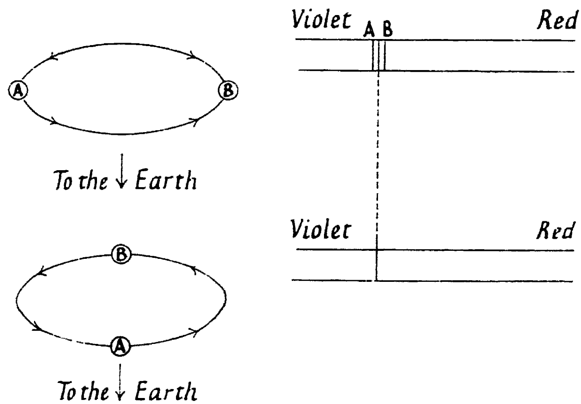


FIG. 25. A spectroscopic binary. In the upper diagram, star A is approaching and star B receding. A therefore gives a violet shift and B a red shift; the lines are moved respectively to the violet and red sides of the mean position of the line (dashed in the picture). In the lower picture the orbital movement of the stars does not involve an approach or recession, and the lines are superimposed in the mean position, as shown.

edge-on to us, there will be times when one star (A) is approaching while the second star (B) is receding; remember that the centre of gravity of the system will be roughly midway between the two. This is shown in the upper section of the diagram. In the second section, the two components are in almost the same line of sight, and the motions will be transverse relative to the Earth.

In the first position, star A will give a violet shift of the spectral lines, while star B will give a red shift. The spectrum lines will thus appear double. In the second position there will be no Doppler shifts;* the lines due to A will be superimposed on those due to B, and the result will be a spectrum which appears perfectly normal.

If, therefore, we come across a star whose spectral lines periodically become double, we may be sure that we are looking at a very close binary. Such is the brighter component of the Mizar pair, as E. C. Pickering found in 1889. The lines appear double at regular intervals, and it can be found that the revolution period of the 'twins' is 20½ days. Another example is Beta Aurigæ, close to Capella, also studied in 1889. Over a thousand of these spectroscopic binaries are now known.

Capella itself is of interest here. In normal telescopes it appears single, but the spectroscope shows it to be a binary; the components are about 80 million miles apart, and have a revolution period of just over 100 days. One star is of type G0, with a mass 4½ times that of the Sun; its F5-type companion has 3¼ times the Sun's mass. Modern instruments have revealed Capella as a visual binary, though of course there are few instruments powerful enough to split it.

We also know of many cases in which the spectrum of the companion is too faint to be seen at all. This means that the lines due to the primary will oscillate to and fro around their mean position—to the violet side when the primary is approaching, to the red side when it is receding.

Binary stars prove to be so common in the heavens that some astronomers regard them as the rule rather than the exception. Less common, though still reasonably frequent, are 'family parties' of stars—triple, quadruple and so on. Mizar is one example. As we have seen, it is a binary, and the brighter component is itself a spectroscopic binary, so that we have three stars in association. But the best example of a multiple star is Epsilon Lyræ, not far from Vega.

Epsilon Lyræ is a naked-eye double, and people with normal eyesight will have no trouble in splitting it when observing conditions are good. The distance between the two components is 208 seconds of arc. A 3-inch telescope will show that each component is again

* There will of course be a general Doppler shift due to the radial motion of the whole binary system, but this can be allowed for, and makes no difference to the general argument.

double, so that we have a true quadruple system. All four stars are similar in luminosity and spectral type; all are considerably more brilliant than the Sun.

The movements of stars in the Epsilon Lyræ system must be decidedly complex. Each close pair has a revolution period of several hundreds of years, but the two pairs take an immense time to complete one circuit round their common centre of gravity. In fact, no positive shift has been recorded, so that the period may well amount to more than a million years.

It is always worth looking at Epsilon Lyræ, since any modest instrument will show it well. Another famous multiple is Castor, the senior but fainter member of the two Twins. A small telescope reveals it as a fine binary; the two components differ in brightness by about a magnitude, and the revolution period is 350 years. Each star is a spectroscopic binary, the periods being three and nine days respectively. At a distance of 73 seconds of arc lies a third member of the system—Castor C, made up of two Red Dwarfs moving round each other in 19 hours. The Red Dwarf pair undoubtedly circles round the main quadruplet, but must take millions of years to complete one journey.

This is certainly a stellar family. Castor is not the single speck of light which appears to the naked eye; it is made up of six separate suns, four brilliant and two dim, arranged in pairs. We may be sure that all six are of about the same age, and were formed by the same process, but they have had very different life-stories.

Yet another complex system—a triple, this time—is that of Alpha Centauri. The main star is a superb visual binary, and Proxima, which has the distinction of being our nearest stellar neighbour beyond the Solar System, is also a member of the family. It moves round the bright pair, but again the period must amount to millions of years. Incidentally, we can tell that it is a genuine member of the Alpha Centauri group, as it shares the motion of the brilliant binary through space.

As final examples of multiple stars, we may turn back to Orion, that magnificent constellation which seems to be able to supply us with anything we may want in the nature of stellar wonders. In the gaseous nebula which marks the Hunter's Sword we find Theta Orionis, known as the Trapezium because of the arrangement of its four chief components. Sigma, between the Nebula and the stars of the Belt, is another multiple, less striking than the Trapezium but still well worth examination.

There is a great fascination in these pairs and groups of stars. Wide or close, optical or binary, coloured or colourless, they can provide the casual observer with endless hours of enjoyment, while the more serious amateur may make himself extremely useful in measuring their separations and position angles.

What if we lived on a planet circling round a binary star? We would have two suns instead of one. There might be a huge Red Giant accompanied by a dim, massive White Dwarf, or alternatively we might be treated to the spectacle of a yellow sun with a blue companion, which would certainly provide us with colour effects beyond the wildest dreams of any artist. It may be, of course, that some such binaries do have planet families, and there is no definite reason why some of these planets may not be inhabited. Unfortunately it is not likely that we will ever know, and we must be content with our own single sun, which sends us so much radiation that we do not always realize that it is nothing more than one of the Galaxy's Yellow Dwarfs.

10

Variable Stars

On the evening of November 12, 1782, an 18-year-old boy named John Goodricke was busy observing the stars. He was a serious astronomer, but an unusual one; he was deaf and dumb, and had been so from birth. Fortunately there was nothing the matter with either his eyesight or his brain.

Goodricke was particularly interested in Algol, or Beta Persei. In the ordinary way Algol is about as brilliant as Mizar or Polaris, but on this particular occasion something was happening to it; it was fading, and continued to do so for several hours until it had dropped to magnitude 3½. Then it started to increase once more, returning slowly to its usual brightness.

Goodricke was not the first to observe this curious behaviour in Algol, since Geminano Montanari, an Italian professor of mathematics, had noticed it as long ago as 1669. Yet nobody had explained it satisfactorily, and Algol was clearly quite different in type from the other known 'variable star', Mira in the constellation of Cetus. Goodricke believed that he had the answer, and in the following year he wrote a paper in which he suggested that the changes in brightness shown by Algol were due to the periodic eclipse of the bright star by a dimmer binary companion.

We know now that Goodricke was right, and it was a tragedy that this gifted deaf-mute should have died soon afterward at the early age of 21. Had he lived, he would have done much for astronomical science.

Algol is easy to find. The best pointer to the constellation Perseus is Cassiopeia; an imaginary line from two of the stars in the W leads us to Mirphak or Alpha Persei, of the 2nd magnitude, and Algol lies not far off. We can also use the stars in Cassiopeia to estimate the changing brightness of Algol. At maximum, Algol is slightly brighter than any of the stars in the W,* while at minimum it is approximately equal to Epsilon Cassiopeiæ, the faintest of the five.

Algol is at maximum for most of the time. For 2 days 11 hours it shines steadily, but then fades down to its least brightness in a period of only 5 hours. After minimum a further 5 hours is needed to regain normal brilliancy, and then nothing more happens for a further 2 days 11 hours. In fact, Algol seems to 'wink' regularly.

The best way to show the behaviour of Algol or any other star which changes in brightness is by means of a light-curve, in which magnitude is plotted against time. Examples are given here. It will be seen that Algol is not absolutely constant for the whole 2 days 11 hours of maximum, but to measure very small changes in brilliancy naturally needs sensitive instruments.

There is a rather interesting point about the name 'Algol', which is Arabic, and means 'the head of the ghul'—a ghul being a female demon with an unprepossessing appearance and even more unprepossessing habits. In classical legend the star is equally sinister, since it marks the severed head of the Gorgon, still carried by Perseus in his journey across the sky. This has led to the suggestion that the ancients knew all about Algol's curious behaviour, and it has been maintained that the star itself was regarded as thoroughly evil. Modern scholars disagree, and it is not now believed that the variability was known in ancient times, but it is certainly appropriate that Medusa's head should be marked by a 'winking' star.

Goodricke's suggestion was reasonable enough, but for a long time nobody could prove it. Sir William Herschel, for instance, examined Algol carefully with his powerful telescopes, but could never see it as anything but a single point of light. This was not surprising, since modern work has shown that the distance between the two components of the binary is not much greater than 6 million miles; the angular separation is too small to be detected visually, and, as usual, we have recourse to the spectroscope.

It appears that the Algol system is decidedly complex, but that the brightest member is of spectrum B8, with a surface temperature

* Actually Gamma Cassiopeiæ, in the W, is itself variable, and may sometimes become brighter than Algol at maximum—though this has not been the case for 20 years now. Alpha Cassiopeiæ is also, probably, a variable star, and is described below.

of 12,000 degrees and a diameter of about 2½ million miles. The second component is larger but dimmer. Its spectrum is of later type, and its surface temperature is considerably less than the Sun's, while the diameter is 3 million miles. Obviously, then, the

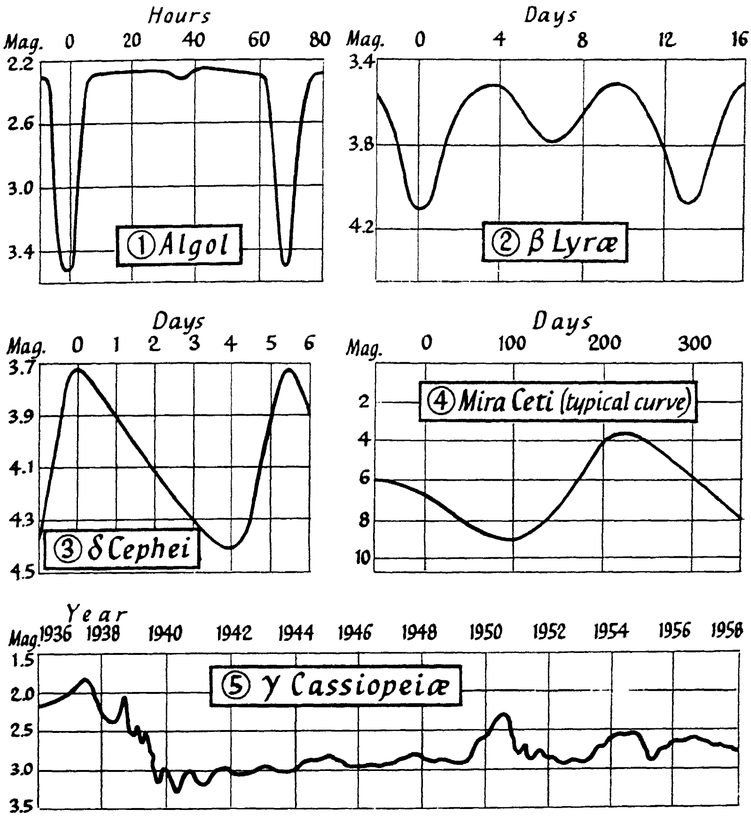


FIG. 26. Light-curves of variable stars: two eclipsing binaries (Algol and β Lyræ), the prototype Cepheid (δ Cephei), a long-period variable (Mira), and a pseudo-nova (γ Cassiopeiæ). The rough curve of γ Cassiopeiæ is drawn from my own estimates, and should not be regarded as at all precise.

principal 'wink'—observed by Goodricke—takes place when the dimmer star (B) passes in front of the brighter one (A) and eclipses it. When A hides B, there is a much slighter fall in brightness which cannot be noticed without special measuring instruments.

Algol A and B revolve together with regard to a more distant component, Algol C; the revolution period is about 1 year 9 months. C has never been seen visually, but its spectrum can be observed, and proves to be either late A or early F type, so that the star is more luminous than Algol B. It is also believed, though without definite proof, that the Algol system includes a fourth member which moves round the bright binary in a period of about 188½ years.

We have met with spectroscopic binaries before—Mizar is a good example—and in point of fact the only difference is that in the case of Algol, the orbit is tilted so that we see its plane almost edge-on. A so-called eclipsing variable is not truly variable at all, and for this reason the term 'eclipsing binary' is to be preferred.

Algol is by no means unique. Many similar eclipsing pairs are known—about 800, in fact—and other Algol-type stars visible without a telescope are Lambda Tauri and Delta Libræ. Two other naked-eye stars in which eclipses occur are well worth mentioning, not because they show obvious fluctuations in the way in which Algol does, but because they are so interesting in themselves. By a coincidence they are near neighbours in our sky, though they have no actual association with each other.

Close to the brilliant Capella may be seen a triangle made up of three faint stars, known popularly as the Hædi or Kids. One, Eta Aurigæ, is entirely unremarkable. The other two, Zeta and Epsilon Aurigæ, are our eclipsing binaries.

Zeta—once dignified by a proper name, Sadatoni, which has fallen into virtual disuse—does not show marked changes in light, and in fact the variations are very hard to detect at all with the naked eye. Moreover the eclipses are infrequent, since the period is 972 days (as against less than three days for Algol). One component is a B8 Main Sequence star, over 100 times as brilliant as the Sun, and with a diameter of some 3 million miles. The companion is a K4-type supergiant with a much lower surface temperature, but with an immense diameter amounting to over 200 million miles, which is larger than that of the Earth's path round the Sun.

The most interesting phenomena occur when the red supergiant eclipses the B8 component. Even before the true eclipse begins, the blue star dims slightly, showing that it is shining through the vast tenuous atmosphere of its companion; for some time after the start of the actual eclipse, the light from the B8 star is still to be seen cutting through the outer layers of the supergiant. This shows

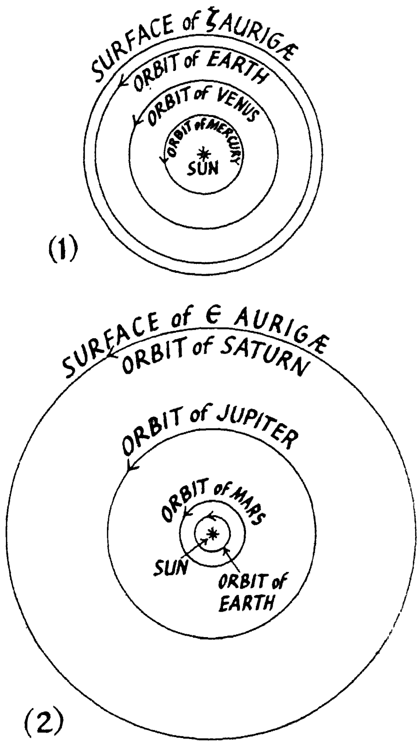


FIG. 27. Sizes of two supergiant stars. (1) the K4-type component of the Zeta Aurigæ system. The diameter is over 200 million miles, which exceeds that of the Earth's orbit round the Sun (186 million miles). Here, the size of the supergiant is shown together with the orbits of the three innermost planets of the Solar System—Mercury, Venus, and the Earth. For the sake of simplicity, the planetary orbits are shown as circular, though actually they are somewhat elliptical.

(2) The larger component of the Epsilon Aurigæ system. Here the diameter is believed to be about 1800 million miles, which exceeds that of the orbit of Saturn round the Sun (1772 million miles). The size of the star is here shown with the orbits of Saturn and other planets round the Sun.

us that the supergiant must be immensely rarefied, with a density of perhaps one five-millionth that of water. At this time the spectrum of the combined pair is highly complex, since we see lines due both to the supergiant and to the blue star, but as the blue star passes behind the supergiant its spectrum is gradually blotted out, to reappear before the end of the eclipse.

Zeta Aurigæ is a fascinating star, and its eclipses are closely studied whenever they occur, but Epsilon Aurigæ is even more remarkable. The variations in light are greater, and were discovered by Fritsch as long ago as 1821, but it was not until much later that the star was found to be an eclipsing binary. The brighter component is a particularly luminous yellow supergiant, with a candle-power about 60,000 times that of the Sun and a diameter of over 150 million miles. The second member of the system is one of the largest stars known to us, since its diameter is about 1800 million miles. This is big enough to hold the orbit of Saturn round the Sun, and yet the star is so tenuous that its total mass is only 18 times the Sun's. The surface temperature is a mere 1200 degrees, which is amazingly low for a star, and nobody has yet actually seen it. Its size is judged from the length of time which it takes to eclipse its companion; the revolution period is 27 years.

Suppose we take a journey in imagination, and suppose that we could go for a flight round the surface of the larger component of Epsilon Aurigæ, travelling in a jet-aircraft which moves at a steady 1000 m.p.h.? Instead of completing one circuit in roughly a day, as would be the case on Earth, we would be in for a very long journey indeed. It would take us about 6300 years, so that if we had started off before the building of the Egyptian Pyramids we would still not have completed one 'lap' of Epsilon Aurigæ.

It is interesting to speculate as to what this tremendous, diffuse globe is really like. Some authorities think it to be an extremely young star, still in the process of condensing out of interstellar matter; but no general agreement has been reached, and we must remember that it is now usually believed that most Red Giants, such as Betelgeux, are well advanced in their careers instead of being stellar infants. Meanwhile, it is apparent that Epsilon Aurigæ is quite exceptional. It may not be the largest star known, since possible rivals are the larger component of another eclipsing binary (VV Cephei) and also the well-known Rasalgethi or Alpha Herculis, but it is well worth looking at, and the smaller member of the system is quite conspicuous to the naked eye. If you go out on any clear night and look for the Hædi, next to Capella, you will be able to recognize Epsilon without the slightest difficulty. It looks so dim and unimportant that it is hard to remember that we are looking at one of the supreme giants of the whole Galaxy.

It would be wrong to suppose that all Algol-type systems are made up of giants or supergiants; in fact the fainter component of Algol does not qualify as a giant, though it is too bright to be in the Main Sequence and is officially classified as a 'sub-giant'. Dwarf pairs exist as well, a good example being the faint component of the Castor system—alternatively known as YY Geminorum—which is an eclipsing binary made up of two Red Dwarfs. UX Ursæ Majoris, in the Great Bear, is different again. The components are not very unequal; each has about half the diameter of the Sun, but each is more massive than the Sun. We can hardly class either as a White Dwarf, but the densities are much greater than for normal stars, and the luminosities are abnormally low. The two components are thus termed 'sub-dwarfs'. The period is only $4\frac{3}{4}$ hours, and eclipses last for a mere 40 minutes. According to the American astronomer G. H. Herbig, the star VV Puppis, in one of the subdivisions of the large constellation Argo, is an eclipsing binary with a revolution period of only 100 minutes; it is made up of a small, very dim star accompanied by a larger one which is intrinsically variable, so that the light changes are very complicated.

Another very famous eclipsing binary is Beta Lyræ, or Sheliak. It is easy to find, since its position close to Vega makes it quite unmistakable, and its neighbour Gamma Lyræ makes an excellent comparison star. The variations in light were discovered in 1784 by Goodricke, only a short time before his death, and are quite unlike those of Algol. At maximum Beta Lyræ shines as a star of magnitude $3\frac{1}{2}$, but there is no period of constant brightness, as changes are always going on. The sequence of events is remarkable. Starting at maximum, the star fades down to below the 4th magnitude; it then recovers to its original value, but when it fades again the minimum is less marked (magnitude $3\frac{3}{4}$). The succeeding minimum is again 'deep', and deep and shallow minima take place alternately.

The cause of this odd behaviour is to be found in the shape of the two components. Both are of type B, and they are so close together that they almost touch. They raise huge tides in each other, and each star is distorted into the shape of an egg; they draw matter away from each other, and some of this matter streams out to produce a shell of gas round the pair. Less than 200 Beta Lyræ type variables are known, but we may also include a similar number of W Ursæ Majoris stars, in which the two components are similarly egg-shaped but are more nearly equal in luminosity.

Much has been learned from the eclipsing binaries, in their various forms from the huge supergiant pairs down to the egg-shaped stars and the faint sub-dwarfs. Yet their apparent changes in brightness are not real, and it is time to pass on to the true variable stars. Of these, the most famous example is Mira Ceti, in the Whale.

On August 13, 1596, David Fabricius, a Dutch pastor, was looking at stars in Cetus when he noted an object of the 3rd magnitude. It looked like a perfectly normal star, but a few weeks later, when he looked again, it had disappeared. This was certainly unusual, but oddly enough Fabricius seems to have made no further searches for it.* Seven years later Johann Bayer was engaged in drawing up his classic catalogue when he again saw the star, and allotted it the Greek letter Omicron. This time it was of the 4th magnitude, and Bayer did not connect his Omicron Ceti with the disappearing star of Fabricius. It was observed now and again between 1603 and 1638, but then another Dutchman, Phocylides Holwarda, commenced a series of observations of it and found that it appeared and vanished regularly. To Holwarda, then, must go the honour of being the first to identify a genuinely variable star.

Mira has a period of approximately 331 days. It is necessary to say 'approximately' because the interval between successive maxima is not always the same, and neither is the greatest magnitude. There have been years when Mira has become as bright or brighter than Polaris; at other maxima the magnitude has not exceeded 5. Actually, Mira is not often conspicuous without a telescope, and is visible to the unaided eye for only about 18 weeks

* Fabricius met with a curious end. In 1616 he preached a sermon in which he hinted that he knew the identity of the member of his congregation who had stolen one of his geese. Evidently his surmise was correct, since he was assassinated before he could divulge the name of the culprit!

out of its 47-week period. However, it is easy to find even when below naked-eye visibility, since it lies in the same low-power telescopic field with a lovely double star, 66 Ceti, whose components are yellow and bluish respectively.

Mira itself is noted for its strong orange-red hue, and this is natural enough, since the spectrum is of type M. When we examine other long-period variables, with periods greater than about 140 days, we see that this is the general rule; we find spectra of M, N, R, S and occasionally K, but seldom do we come across earlier types. This means that the long-period stars are generally orange or red in tint.

Mira has its own points of interest. It is a supergiant even larger than Betelgeux; it is 250 light-years away from us, and is accompanied by a faint companion which is either a White Dwarf or else a curious kind of sub-dwarf. When the variable reaches minimum, it sinks below the 8th magnitude, so that it is by no means a prominent object.

Another long-period variable, different in type from Mira, is Eta Geminorum, which lies roughly between Castor and Betelgeux. Here the magnitude range is 3·3 to 4·2—less than one magnitude, as against six for Mira—and the period is 231 days. It too is a red M-type star, and may be compared with its near neighbour Mu Geminorum, which also is reddish but which does not vary perceptibly. More difficult is Chi Cygni, in the Swan, between Albireo and the centre of the 'cross'. The 4th magnitude star Eta Cygni is always to be seen, and when near maximum Chi may also reach this brilliancy, but at minimum it sinks to the 14th magnitude, and is then beyond the range of any but powerful telescopes. The period is 409 days.

Generally there is no law about the alterations in period, and we can never quite forecast how stars such as Mira will behave. There are, however, a few cases of systematic change in period. R Hydræ, not far from the 3rd magnitude star Gamma Hydræ, had a period of about 500 days when its variations were first detected by the Italian astronomer Maraldi in 1704, but nowadays the interval between successive maxima is only about 400 days. Whether this represents a real and permanent evolutionary change in the star, we do not know.

The spectra of Mira and similar stars show emission as well as absorption lines. Not all these red variables, however, are of type M, since about 10 per cent. of them belong to the latest spectral types—R, N and S. The N-stars are the reddest of all, and are known as carbon stars because lines due to this element and its compounds are so prominent in their spectra. Only one of them is visible to the naked eye—U Hydræ, which changes from magnitude 4½ to 6½ in a period of rather less than 200 days. In general, these very late-type stars are extremely remote, so that they are uncommon in our own particular part of the Galaxy.

What makes these long-period stars vary?

There is no doubt whatsoever that the changes are intrinsic, and are not due to eclipse by a binary companion as with Algol or Beta Lyræ. The total luminosity changes, and so does the diameter, so that the star appears to pulsate as it swells out and then shrinks again. The exact mechanics of it all are still doubtful, but it may be that the crux of the matter is a sort of tug-of-war between two opposing forces: gravitation, which is tending to make the globe contract, and the pressure of the gases making up the star, which tend to make the globe expand. With a variable, these two forces vary, leading to the pulsations observed. The theory seems reasonable enough, but there are many complications to be taken into account, and the full answer is certainly by no means straightforward.

Linked with the long-period stars are the irregular and semi-regular variables. Eta Geminorum is sometimes placed in this class, but the most famous member is undoubtedly Betelgeux. As with Mira, we have a shrinking followed by a swelling, and the luminosity output and the diameter show alterations, but there is no definite period, and the most we can say is that there is a rough cycle of about five years. The range does not exceed 1½ magnitudes, but the slow variations may be followed easily enough simply because Betelgeux is always so bright. I have seen it equal to Rigel, while at minimum it is not much superior to Pollux. The best way to watch its changes is to compare it with Aldebaran, which is of roughly the same colour.

Mu Cephei, Sir William Herschel's so-called Garnet Star, is of similar type. Unfortunately it is not conspicuous without a telescope, since it is always below the 3rd magnitude; but it never sets over Britain, and once you have identified it you will always be able to find it again without any trouble. Binoculars bring out its vivid hue excellently.

Other variables seem to have no period at all. Some remain at maximum for most of the time, and drop to minimum at irregular intervals; others do the reverse, being generally faint but showing unpredictable rises from time to time. Half a dozen stars, of which the best-known is Z Camelopardalis in the obscure constellation of the Giraffe, normally show semi-regular increases and falls, but sometimes become perfectly steady for months on end before starting to fluctuate again. Then, too, there are about 25 known 'symbiotic' stars such as Z Andromedæ, where emission lines indicating high temperature are superimposed upon a background low-temperature type spectrum, usually of type M. The inference is that two objects of entirely different kinds are placed close together in conditions of extraordinary interdependence and adjustment, and a complex shell-structure may be at least part of the answer. AG Pegasi, in the Flying Horse, may belong to the symbiotic class; it used to have a B-type spectrum, but since about 1922 it has gradually developed M-type characteristics as well, and the spectrum and brightness changes have provided astronomers with a constant headache.

Most of these curious objects are faint and far away, but there is one extraordinary star which deserves special mention because it is a prominent naked-eye feature of the sky. This is Gamma Cassiopeiæ, the middle star of the W. It has an interesting history, and I have a somewhat fatherly interest in it because I noticed its variation when I was a schoolboy of 13. I can claim no credit—the discovery had been made by others long before I noticed it!—but at the time I was quite unaware that there was anything strange about the star; I was using it as a comparison for its neighbour Alpha Cassiopeiæ, which is suspected of showing irregular fluctuations between about magnitude 2 and 2½.

All early catalogues gave the magnitude of Gamma as 2·25, very slightly fainter than Polaris, but in 1936 it began to increase, and by the middle of 1937 had brightened up to magnitude 1·6. A year later it was back to its original magnitude, but instead of stopping there it continued to fall, until by the end of 1939 it was no brighter than magnitude 3. For the last few years it has hovered between $2\frac{1}{2}$ and $2\frac{3}{4}$.

The oddest thing about Gamma Cassiopeiæ is its spectrum, which is classed as Bo, but which is decidedly peculiar. Emission as well as absorption lines are seen, and the spectrum is itself variable. There have been suggestions that all the changes are due to disturbances in the star's upper atmosphere, but nowadays it is considered more probable that the causes of fluctuation are more deep-seated.

Lastly let us consider the case of R Coronæ Borealis, in the small but well-marked constellation of the Northern Crown, near Arcturus. Ordinarily the star is a bright telescopic object, but at irregular intervals it fades abruptly, sometimes by as much as 8 magnitudes, remaining at minimum for a brief period before climbing back spasmodically to its former eminence. It is the prototype of a group of stars including about a dozen members, all of which show prominent carbon lines in their spectra. When fading begins, the spectra remain more or less unaltered for some time, but near minimum some of the dark lines are replaced by bright lines. This presents astronomers with serious problems, and some authorities refuse to believe that R Coronæ and its companions are normal variables at all; instead, it is suggested that they may be periodically veiled—not by a darker star, as with Algol, but with interstellar material of some sort. So far the puzzle remains unsolved.

We have described the long-period and irregular variables, but we have yet to mention the Cepheids, which are by far the most important of all so far as we are concerned. They take their name from Delta Cephei, whose changes in brightness were discovered in 1784 by the keen-eyed Goodricke. The chart on page 49 shows how to find it; fortunately two stars of the W of Cassiopeia show the way to it, and it is easily identified because it forms a small triangle with its neighbours Epsilon and Zeta Cephei. The magnitude alters from 3·7 to 4·3 in a period of 5 days 9 hours, and the period is absolutely regular, so that it may be determined to within less than a second. The light-curve is not completely smooth, as the increase from minimum to maximum is steeper than the subsequent drop, but we can always tell how bright Delta Cephei will be at any particular moment.

Here again we are dealing with a pulsation; in fact the pulsation theory was first worked out to explain changes of the Cepheid type, and is not so precisely applicable to the long-period stars such as Mira. The temperature changes, and so of course does the spectrum. At times Delta Cephei itself resembles a star of class F4; at other times it becomes G6, so that it is then cooler and yellower. The surface temperature drops, indeed, by as much as 2000 degrees.

Other naked-eye Cepheids are known, the best examples being Eta Aquilæ and Zeta Geminorum in the northern hemisphere and Kappa Pavonis in the southern. There are hordes of telescopic Cepheids, with periods ranging from just under 2 days up to 45¼ days in the case of an interesting star known as VY Vulpeculæ, in the little constellation of the Fox. In some cases the magnitude range is very small. For instance, Polaris is a Cepheid with a period of 3·97 days, but the alteration in magnitude is so slight that it is undetectable without instruments.

As well as these 'classical Cepheids' there are various sub-groups, in which the behaviour is not the same as that of Delta Cephei and yet there are obvious points of resemblance. The RR Lyræ stars have shorter periods, less than an hour and a half in the case of CY Aquarii, and there are also less regular short-period variables named after the class prototype, RV Tauri. Yet another sub-class includes the conspicuous naked-eye stars Beta Canis Majoris and Beta Cephei, where again the changes in brilliancy are very small. All these latter are hot bluish stars, and it has been suggested that their periods are increasing slightly, perhaps by about one second per century—in which case we are measuring what must be definite progress in the stars' evolution.

The importance of the ordinary Cepheids lies in the fact that there is a definite law connecting their periods of variation with their real luminosities. The rule is: the longer the period, the greater the average luminosity of the star—so that for instance Zeta Geminorum (period 10·1 days) is more luminous than Delta Cephei itself (period 5·4 days). The reason for this link is quite unknown, but it is undoubtedly valid. It applies only to the classical

Cepheids, while the RR Lyræ stars all appear to be of about the same luminosity, 90 times that of the Sun.

We will return to the Cepheid period-luminosity law later, but meanwhile it is worth mentioning some of the bright naked-eye stars which although not variable in the generally accepted sense of the word, seem to have altered in brightness since first catalogued. The best example is Megrez or Delta Ursæ Majoris, in the Plough. Its present magnitude is 3·4, so that it is more than a magnitude fainter than Mizar; yet apparently it used to be at least nearly equal to the other Plough-stars, so that it may have faded since Ptolemy's time. Even now it is suspected of occasional fluctuations, so that it may be an irregular variable which remains steady for years at a time. Castor in Gemini used to be ranked superior to its 'twin' Pollux, but is now half a magnitude fainter; the southern star Theta Eridani, the 'Last in the River', was estimated as of the 1st magnitude in Greek times, but is now below the 3rd; Denebola or Beta Leonis has likewise fallen from the 1st magnitude to below the 2nd, and there are various other examples. On the other hand Rasalhague in Ophiuchus, ranked of only the 3rd magnitude by Ptolemy, is now of the 2nd, and it is particularly interesting to find that Beta Canis Majoris, which we know as a short-period variable with small range, is also a magnitude brighter than as given by Ptolemy. We must beware of placing too much trust on ancient estimates, but the discrepancies deserve to go on record.

Can the Sun be regarded as a variable star? Strictly speaking, no; its output of light and heat remains virtually constant, which is very lucky for us, since even a small alteration would result in our being boiled or frozen. Yet we know that there is a semi-regular solar cycle of about 11 years, and that the numbers of sunspots wax and wane in a marked manner. This may or may not be the case with other stars, and there is no certain way of finding out as yet.

According to one theory, all stars go through a stage of evolution when they fluctuate in light. This again may or may not be so, and we are not likely to come to any decision until we have worked out a more accurate pattern for the life-story of a star.

Meanwhile, we can see that these variables are among the most intriguing objects in the heavens. They are of different kinds—the 'fake' variables such as Algol, which prove to be nothing more than eclipsing binaries; the long-period stars such as Mira, the punctual and highly-reliable Cepheids, and the erratic variables which are always apt to spring surprises on us. It has justly been said that variable star work is among the most fascinating of all branches of observational astronomy.

11

Temporary Stars

In the early hours of the morning of December 13, 1934, a British amateur astronomer, J. P. M. Prentice, was busy observing meteors. A meteor, as most people know, is a tiny body moving round the Sun like a dwarf planet; if it enters the Earth's atmosphere it will destroy itself in the streak of luminosity which we call a shooting-star. Each December at around this date the Earth passes through a swarm of meteors, and the result is a shooting-star shower known to astronomers as the Geminids. It was these Geminid meteors in which Prentice was particularly interested.

He watched for some time, recording meteors whenever they appeared. After a spell of observation lasting for three hours or so he felt his eyes becoming slightly tired, and decided to rest by taking a brief stroll and looking casually up at the sky.

In his own words, 'I had not walked three paces before I noticed that there was something wrong with the head of Draco.' The stars which make up the Dragon's head, close to Vega, are not particularly bright, but they form a distinctive pattern, and Prentice noticed that on this occasion there was an extra star in the group, shining clearly at about magnitude 3½. There could be no doubt that the star was new. Prentice went straight to his car, drove to the nearest town—Stowmarket—and telephoned Greenwich Observatory.

Stars of this sort do appear now and then. They blaze up suddenly, taking only a few days or in extreme cases only a few hours to become brilliant; they remain conspicuous for a limited period, which may amount to as much as a month or two, and then sink back into obscurity. They are popularly known as Temporary Stars, but their official designation is 'novæ', from the Latin word for 'new'. Since Prentice's star lay just outside Draco, and within the boundaries of the neighbouring constellation Hercules, it was called Nova Herculis. It is still visible, though very faint, and has now received the permanent designation of DQ Herculis.

Stories of novæ go back for many centuries, and it has been suggested that Hipparchus, the great Greek astronomer of antiquity, drew up his famous star catalogue after his attention had been drawn to the skies by a brilliant nova. (Whether this story is true or not is open to question, but at least it sounds plausible.) In A.D. 173 the Chinese saw something curious in the southern part of the sky, and recorded that 'a star appeared between Alpha and

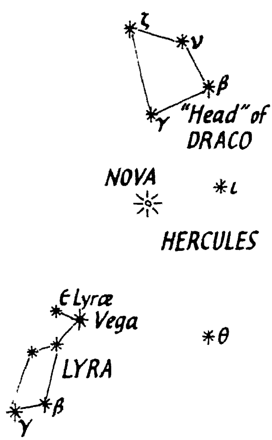


FIG. 28. Position of the 1934 nova in Hercules (DQ Herculis). The star was situated roughly between Vega and Gamma Draconis, just inside the borders of Hercules. While bright, it completely altered the look of the area, since no brilliant stars were nearby.

Beta Centauri, and remained visible seven or eight months; it was like a large bamboo mat, and displayed five different colours'. Like so many of the old records, this description is hopelessly exaggerated, and all that the Chinese can have seen is a brilliant point of light, but a nova may well have been responsible.

Another nova appeared in 1054, again recorded by the Chinese, and this time there can be no doubt about the reports, since we can still see the remains of the outburst. Equally famous was the star seen in 1572 by no less a person than Tycho Brahe, later to become the most famous astronomer of his time, but then an unknown young man in his twenties. Tycho's own description of his discovery, on November 11, is worth quoting:

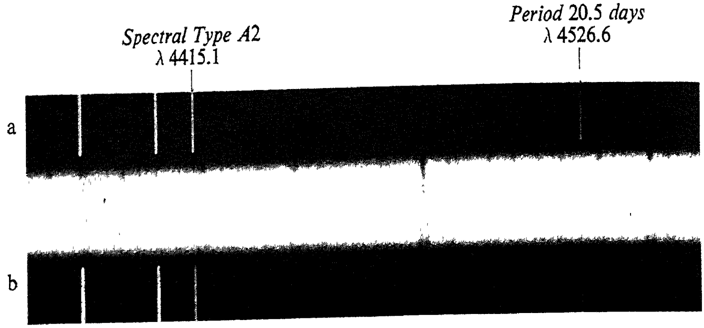
> 'In the evening, after sunset, when, according to my habit, I was contemplating the stars in a clear sky, I noticed that a new and unusual star, surpassing all the other stars in brilliancy, was shining almost directly above my head; and since I had, almost from boyhood, known all the stars of the heavens perfectly (there is no great difficulty in attaining that knowledge), it was quite evident to me that there had never before been any star in that place in the sky, even the smallest, to say nothing of a star so conspicuously bright as this. I was so astonished at this sight that I was not ashamed to doubt the trustworthiness of my own eyes. But when I observed that others, too, on having this place pointed out to them, could see that there really was a star there, I had no further doubts. A miracle indeed, either the greatest of all that have occurred in the whole range of nature since the beginning of the world, or one certainly that is to be classed with those attested by the Holy Oracles.'

Tycho was astonished mainly because it was then believed that the skies must be changeless—and yet here was evidence of a very marked alteration among the stars. The object lay in Cassiopeia, and when at maximum shone more brilliantly than Venus, so that it could be seen even in broad daylight. Slowly it faded, and Tycho, who was as enthusiastic about astrology as about astronomy, did not fail to point out that the effects on humanity would be dire:

> 'The star was at first like Venus and Jupiter, giving pleasing effects; but as it then became like Mars, there will next come a period of wars, seditions, captivity and death of princes, and destruction of cities, together with dryness and fiery meteors in the air, pestilence, and venomous snakes. Lastly, the star became like Saturn, and there will finally come a time of want, death, imprisonment and all sorts of sad things.'

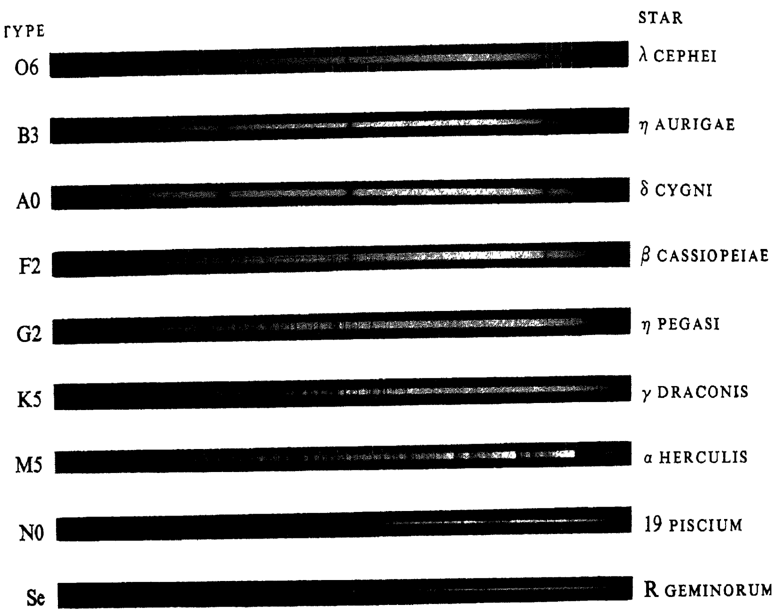
Tycho's astrological predictions did not come true, and indeed it was already becoming generally recognized that astrology is a mixture of over-credulity and fraud. However, his astronomical observations were extremely accurate, and so we know just how

Galaxies in collision. NGC 4038 and 4039. 48-inch Schmidt photograph.

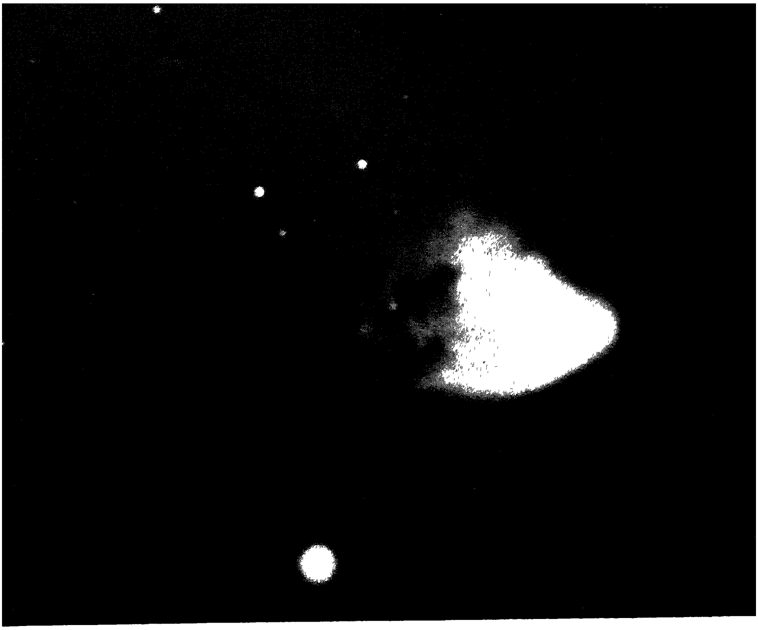


Spectrum of a spectroscopic binary star Zeta Ursæ Majoris (Mizar)

(*a*) *June* 11, 1927. *Lines of the two components superimposed.*
(*b*) *June* 13, 1927. *Lines of the two components separated by a difference in orbital velocity of* 140 *km sec.*

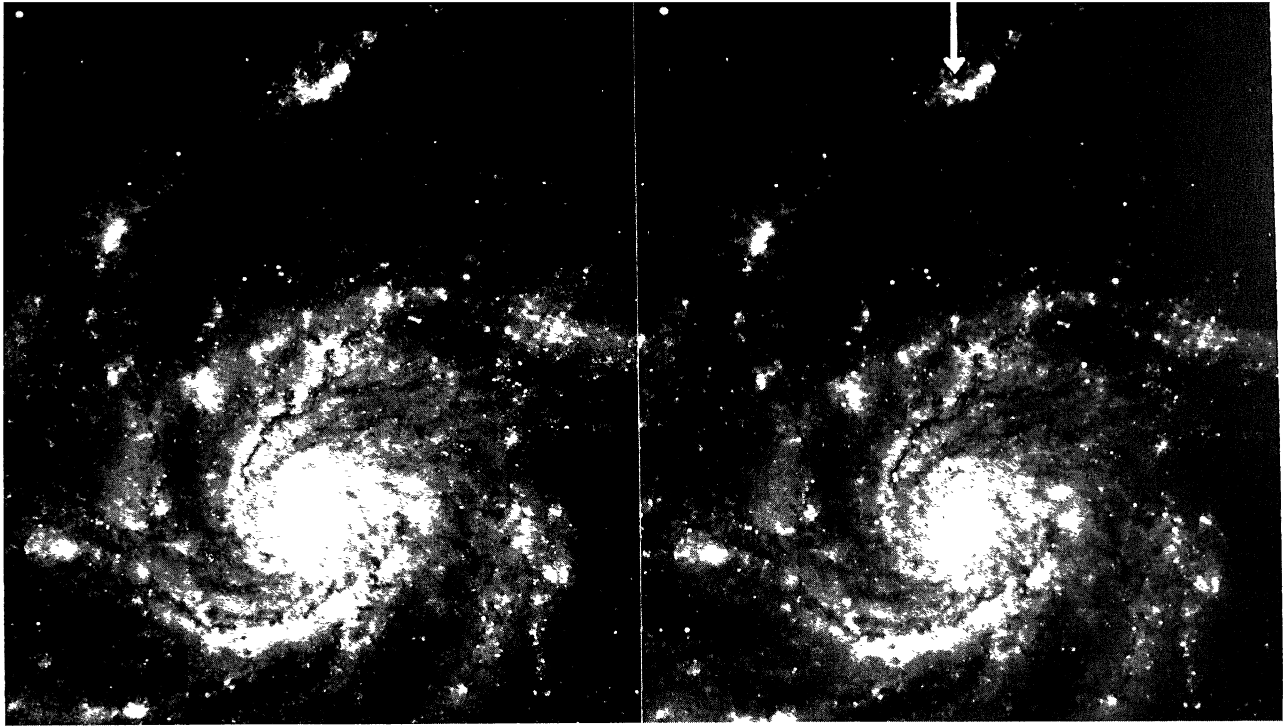


Principal types of stellar spectra

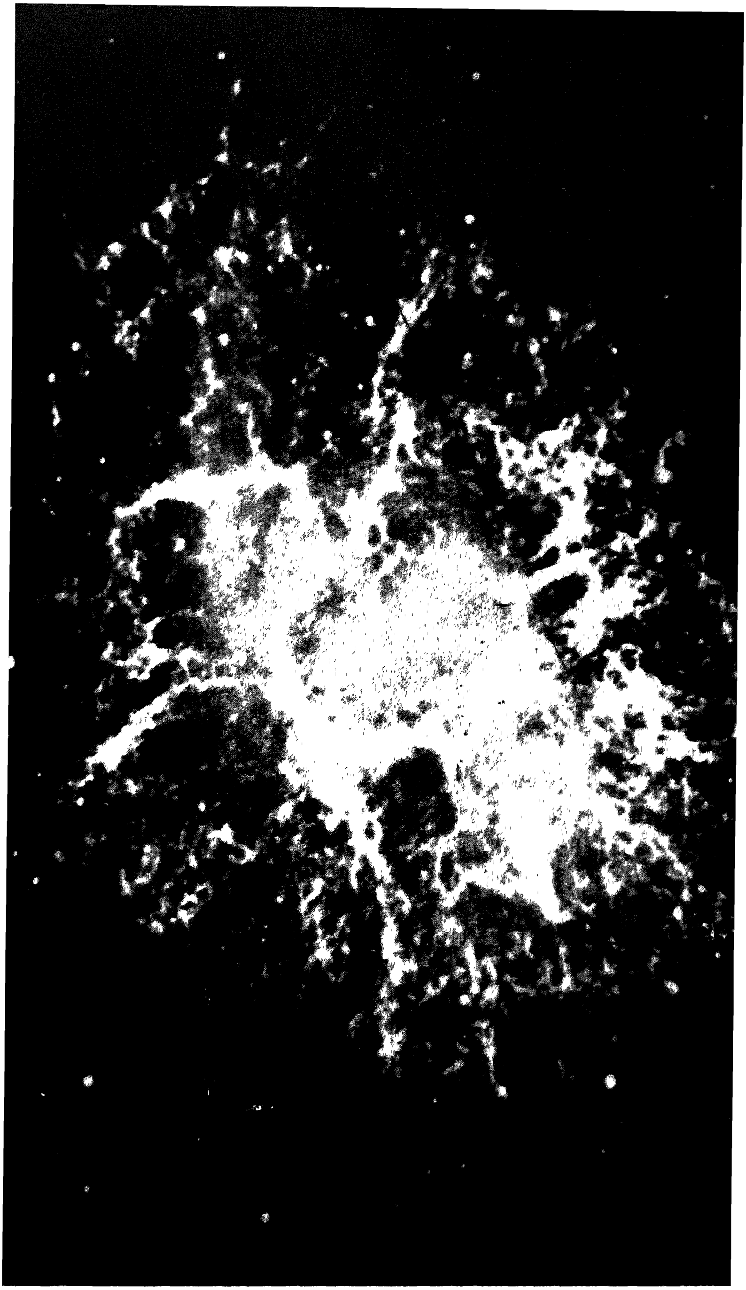


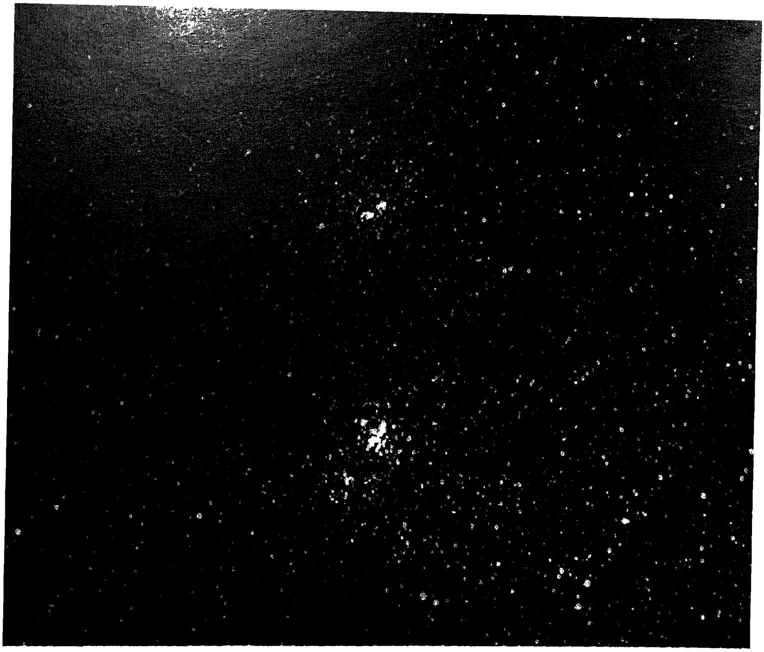
Hubble's variable nebula in Monoceros. NGC 2261. 200-inch photograph.

Expanding nebulosity round Nova Persei. 1901. 200-inch photograph.



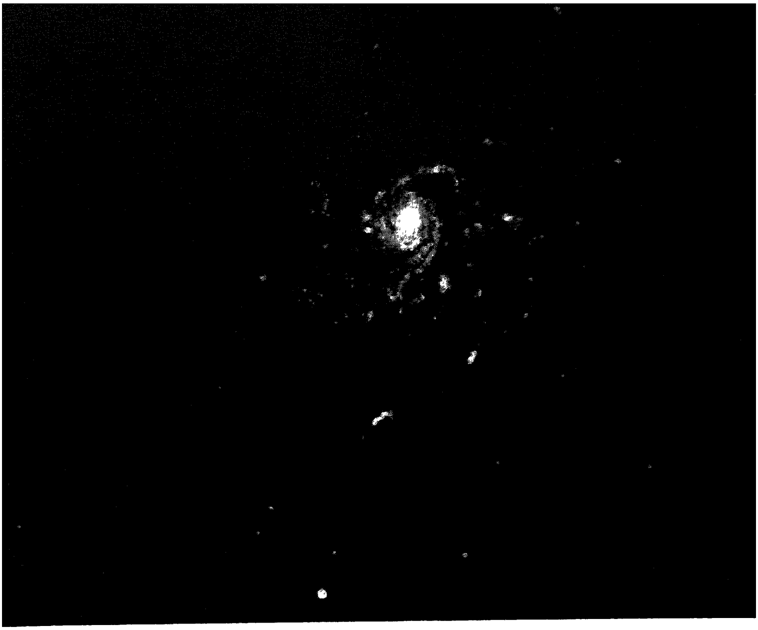
Supernova in M.101. The nova is visible in the right-hand picture. 200-inch photograph.





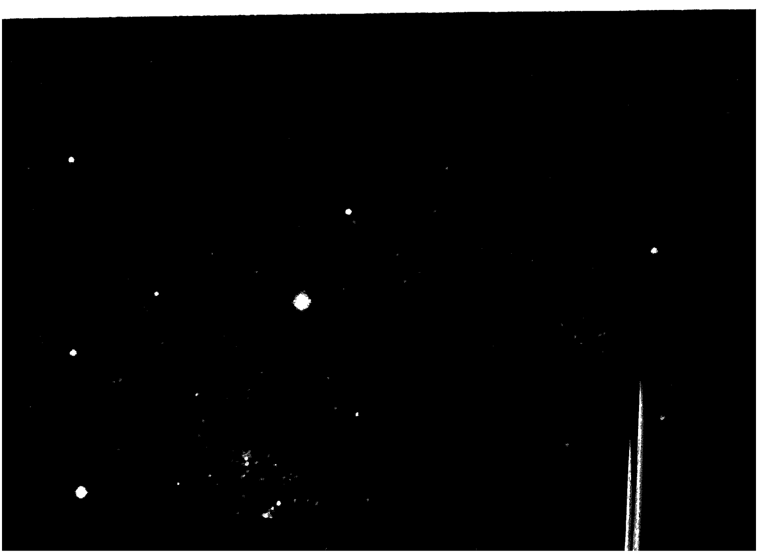
The Double Cluster in Perseus. H VI 33-4 ('Sword-handle').

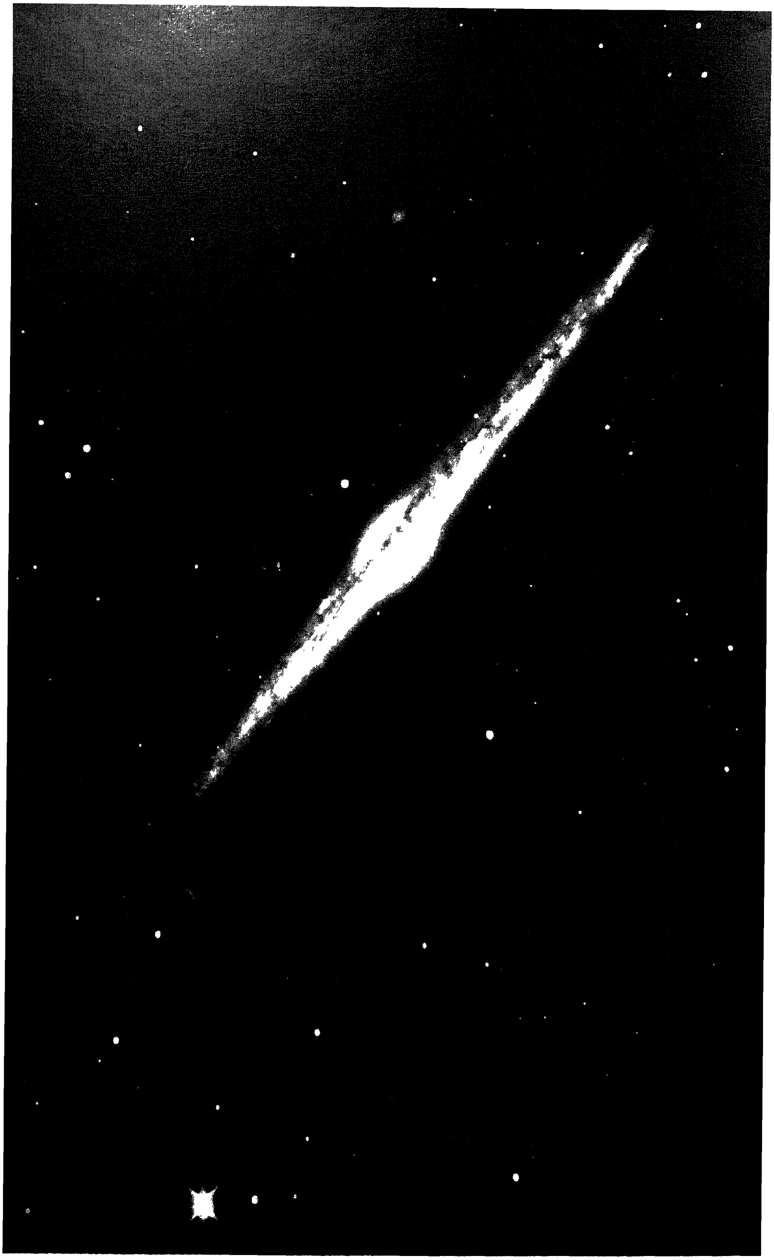
Satellite galaxy of the Andromeda Spiral. NGC 205. 200-inch photograph.



Spiral galaxy. M.101 Ursæ Majoris. Photograph: Ritchey, 1910.

Dwarf galaxy in Sextans. 200-inch photograph.





Galaxy, NGC 4565. 200-inch photograph.

the nova behaved. As soon as it sank below the 6th magnitude it was lost to view; telescopes had not then been invented, and so even Tycho could follow the star no further.

Another brilliant nova appeared in October 1604, in Ophiuchus. It was observed—though not discovered—by Kepler, and remained visible with the naked eye until March 1606. At maximum it was about as bright as Jupiter, so that it far outshone any normal star. It too was lost to view as soon as it became fainter than the 6th magnitude.

Then came the telescope. Little more than 5 years after the appearance of Kepler's nova, Galileo first turned his tiny 'optick tube' to the skies, and found that he could see stars so faint that they were quite invisible to the naked eye. However, no more novæ were seen for many years, and it is a fact that the stars of 1572 and 1604 were much more brilliant than any which have appeared since. A 3rd magnitude nova was seen in 1670 in the little constellation of Vulpecula, the Fox, and another one in 1783 in the neighbouring group of Sagitta, but only during the last 100 years has it become plain that novæ are by no means so rare as used to be thought. Few become bright enough to be seen without a telescope, but fainter examples are relatively commonplace. In 1936 there were no less than four; two in Aquila, one in Sagittarius, and one in Lacerta the Lizard, close to the Great Bear. Of these, only Nova Lacertæ was conspicuous; at its brightest it surpassed Polaris, but it faded quickly.

It is probably worth listing the really important novæ of our own century. There are several of them: Nova Persei 1901 (greatest magnitude 0·0), Nova Aquilæ 1918 (−1·1, brighter than any star apart from Sirius), Nova Cygni 1920 (2·0), Nova Pictoris 1925 (1·1), and Nova Argûs 1942 (0·4); as well as the 1936 star in Lacerta and Prentice's spectacular DQ Herculis of 1934. The list is quite impressive, but it must be added that the 1925 nova—known nowadays as RR Pictoris—was too far south to be visible in Britain, while Nova Argûs was badly placed for observers in our latitudes.*

* The vast constellation of Argo Navis has been split up, and since the 1942 star lay in that part of it known as Puppis (the Poop) it is frequently referred to as Nova Puppis.

Prentice is not the only amateur astronomer to have discovered a nova; the 1901 star in Perseus was found by Dr Anderson, a Scottish clergyman, and there are several other instances. As one never knows when or where a nova will appear, the only condition being that the Milky Way zone is most favoured, the amateur has in fact a certain advantage over the professional astronomer, who is less prone to casual star-gazing. On the other hand, it is wise to be wary of reporting a 'new star' without very careful checking. I was once telephoned in the middle of the night by an enthusiastic observer who told me that he had discovered a bright nova in Scorpio, but fortunately I needed no star map to tell me at once that he was looking at the planet Saturn!

Nowadays we know much more about novæ than Tycho or Kepler could ever learn. To begin with, the name itself is misleading, since a nova is not a completely new star at all. What happens is that a formerly very faint star suffers an outburst which leads to a sudden, temporary increase in luminosity. When the outburst is over, the star sinks back to its former obscurity. It is tempting to suggest that we are watching a simple collision between two stars, but—as is so often the case—the straightforward answer does not fit the facts. The stars are so widely spaced that direct collisions must be very rare indeed, and novæ, as we have found, are not particularly unusual.

One difficulty facing astronomers is that little is known about novæ before they flare up. By the time they attract attention, the outburst has already begun, and it is not often that spectra of the original star can be found, though in one or two cases we have been lucky; Nova Aquilæ 1918, for instance, had an A-type spectrum before its sudden burst of glory. However, once a star has become a nova its later history is closely studied, and it is found that generally the magnitude returns to about its original value, showing that no lasting damage has been done to the star. Yet the increase in luminosity is tremendous; a nova may outshine the Sun 100,000 times or more, and it has been estimated that when at its maximum Nova Argûs 1942 sent out as much radiation as 1,600,000 Suns. Compared with this, the fluctuations of normal variable stars such as Mira and Delta Cephei seem very minor.

There is no doubt whatsoever that a noval outburst is due to a disturbance inside the star, but we have only vague ideas as to the fundamental cause. It is possible that a gradual change in conditions in the star's 'power-house' may lead to the production of excess energy, and if this energy cannot get free it may cause an outburst violent enough to blow material away from the star's surface. Several novæ have developed gas-clouds round them. Nova Aquilæ 1918 is a case in point. A few months after maximum a tiny disk was seen round the star, and this disk gradually increased in size year after year, becoming fainter as it did so; after 1941 the gas-cloud grew so dim that it could not be studied further, but there is every reason to think that it still exists. Even more interest-

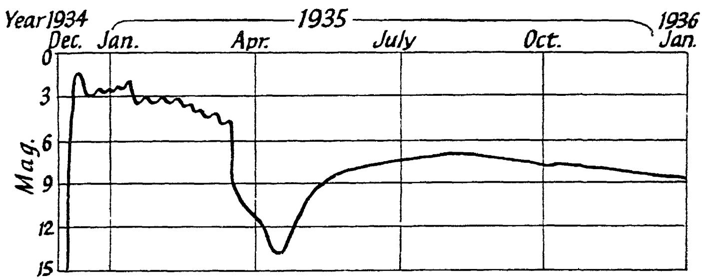


FIG. 29. Light-curve of Nova (DQ) Herculis 1934 in the months following its outburst.

ing was the shell seen round Nova Persei 1901, for in this case the shell was not symmetrical with respect to the star.

Nova Persei had previously shown another interesting feature. Some months after maximum it was found that nebulosity seemed to be appearing to one side of the star, and that this nebulosity was expanding at a tremendous rate. Later measurements proved the apparent expansion to be so rapid that it was simply unbelievable, and some other explanation had to be found. Suppose that Nova Persei were situated inside a dark nebula, previously invisible to us? The flare-up would be a source of intense radiation; this radiation would spread out from the star at the usual 186,000 miles per second, the speed of light, and would illuminate more and more of the nebula each year.

True expanding shells are in a different category, and the velocities are less, though still staggering according to our everyday standards. The record seems to be held by Nova Lacertæ 1936, which threw off material at a 'mere' 2400 miles per second.

Two modern novæ, RR Pictoris and DQ Herculis, are now known to be binaries. DQ Herculis is particularly remarkable. It is an eclipsing system with a period of only 4 hours 39 minutes, and in addition the old nova itself seems to be fluctuating quickly within a small magnitude range. The spectrum is made up of a continuous background, crossed by emission lines which are produced partly in the large expanding nebulous envelope blown off during the 1934 outburst and partly in a much more compact nebula surrounding the old nova. The companion star has never been seen, but is believed to be an M-type dwarf, while the old nova is probably so dense that it is not unlike a White Dwarf. It is a tremendous pity that we have no record of the spectrum of DQ Herculis before its flare-up.

There is no harm in trying to draw up a picture of what happens to a nova during its outburst. The picture may or may not be correct, but at least it may not be very wide of the mark, and all we can do is to make intelligent guesses based upon what evidence we have.

We begin with a star which seems to be perfectly normal, yielding a conventional spectrum. Then its surface starts to swell; in the spectrum, the usual rainbow background and narrow absorption lines are joined by emission lines, displaced to the violet because the blown-off material is moving toward us. The star grows brighter and brighter, and now the emission lines dominate the scene—and then the climax comes. The outbreak has reached its peak, and the radiation pours into space with a fierceness which we cannot comprehend. The star's surface is in upheaval, and material is hurled out at speeds of thousands of miles per second, so that if there were any planets within range they would meet with a tragic end. Then, gradually, the star quietens down. By now the spectrum is like that of a gaseous nebula, but as the outburst subsides the emission lines fade away, and the nebula itself slowly dims until it is lost to view. The brief spell of glory is over, and at last the star returns to its old state.

Of course, different novæ have different ways of behaving. DQ Herculis, which was unusual in many respects, seems to have thrown off no less than eleven shells, and its decline was much more gradual than with most novæ. It remained visible to the naked eye for some months, and at one period it shone with a decidedly greenish hue.

We are still rather in the dark as to the exact cause of the disturbance inside the star, and it would be helpful if we could study a nova at comparatively close range, but unfortunately even DQ Herculis, the nearest of modern bright novæ, is 800 light-years away. (This means that the flare-up seen in 1934 actually took place about 1134, when Englishmen were still living who remembered William the Conqueror.) Is there, then, any chance that a nearby star will be co-operative enough to turn into a nova—and is there any possibility than the Sun itself will suffer some such outburst?

Astronomers are notoriously enthusiastic, but certainly not enthusiastic enough to hope for this. If the Sun became a nova, the Earth would be wiped out of existence at once. Fortunately for us, any such thing is most improbable, since from the little we do know about novæ in their pre-outburst stage it seems that the Sun is simply not the right kind of star.* If an object only a few light-years away became a nova we would be treated to a magnificent spectacle, and 'night would be turned into day' for a short period, but by the law of averages nothing of this sort is likely to happen more than once in millions of years.

On the other hand, there are certain peculiar stars which have undergone more than one noval outburst in modern times. The most spectacular of these lies in the Northern Crown, and is known as T Coronæ. In 1855 Argelander, a German astronomer who compiled a particularly good star-catalogue, recorded it as being of about magnitude 10, but in 1866 it suddenly brightened up to the 2nd magnitude; it was regarded as an ordinary nova, and faded in the usual way, but in 1946 it increased again, this time reaching magnitude 3. Similarly, a fainter star known as RS Ophiuchi became a nova in 1898 and again in 1933. There are also a few stars which have been 'caught in the act' three times.

* If the politicians who 'lead' us are allowed to continue muddling along in their present dangerous fashion, there is a much greater chance that the simultaneous explosion of quantities of nuclear bombs will turn the Earth into a sort of ersatz nova. This will be our own fault.

Even odder is Eta Argûs, in the keel of the Ship. Nowadays it is dim enough, and cannot be seen at all without a telescope, but it has certainly known glory. Before 1820 it was generally reckoned as an easy naked-eye object; in 1837 and the first months of 1838 it shone more brilliantly than any star in the sky apart from Sirius and possibly Canopus, and it was still of the 1st magnitude in 1856. By 1867 it had dropped to the limit of naked-eye visibility, and has remained faint ever since, though its light is not steady. Unfortunately it is too far south to be seen from Britain. P Cygni, in the Swan, is another star which has shown erratic variations of much the same kind, though the magnitude has never risen above 3.

It is not easy to tell whether we are to class the recurrent novæ and the extraordinary Eta Argûs-type stars as true novæ or as unusual variables. Meanwhile, it has been suggested that there is a link between the recurrent novæ and irregular variables such as SS Cygni and U Geminorum, which seem to undergo very mild nova-like outbursts several times a year. Of course, the magnitude changes are much less, and we do not find the tremendous gas-shells shown by proper novæ, but the connection may be there; until we know more about the cause of these stellar explosions, it is hard to decide one way or the other.

So far we have been discussing normal novæ, which involves the sudden flare-up of a star without causing any drastic alteration in the star itself. Now and again, however, we can see explosions which are on an even more colossal scale, and are aptly termed 'supernovæ'.

One of the most famous objects in the sky is the Andromeda Galaxy. To the unaided eye it looks like a faint, misty patch of light; large telescopes reveal it as a true stellar system, now known to be even larger than the Galaxy in which we ourselves live. Its distance from us is about 2 million light-years, and it contains objects of all sorts, including variable stars. In 1885, astronomers were surprised to see a 6th-magnitude nova in it. The discovery was made by an Irish amateur, Isaac Ward, and independently by a Hungarian baroness named De Podmaniczky; it attracted a good deal of attention, mainly because at that time the Andromeda Galaxy was still believed to lie inside our own Milky Way. It was believed that the nova had simply appeared in the same line of sight as seen from the Earth, in which case it must have lain between the nebula and ourselves. It faded quickly, and was soon lost to view in the general blur.

We now know that the nova actually was inside the Andromeda Galaxy. Since it shone brightly enough to be visible to the naked eye across a 2 million light-year gap, it was clearly very luminous, and calculations show that at maximum it was equal to over 200 million Suns put together. A supernova seen in 1937 in a much more remote galaxy was even more violent, and seems to have equalled 350 million Suns for a short period.

This is stellar activity on a grand scale, and is quite different from a conventional nova. A supernova 100 light-years away from us would shine more brightly than the full moon. In such cases we are dealing not with the mere throwing-off of shells of gas, but with a radical change in the star concerned.

Supernovæ are very rare, and during the last thousand years only three have occurred in our own Galaxy. The 1054 star seen by the Chinese was certainly one; so was Tycho's star of 1572, and possibly Kepler's of 1604, though about the latter there are reservations. The most fascinating is certainly the supernova of 1054. The star itself has gone, but in its place even small telescopes will reveal a curious gas-patch known as the Crab Nebula—easy to find, since it lies near the 3rd magnitude star Zeta Tauri, and well worth looking for, though it is not spectacular except in large instruments. It is about 4000 light-years away, and has a diameter of 3 light-years. Even now, the gas is still spreading outward from the old explosion-centre.

Supernovæ are probably the most incredible objects known to us. They are seen fairly often in external galaxies, but in any one galaxy the frequency is extremely low, so that we are not likely to have the chance of studying a local one.

The main distinction between a supernova and an ordinary nova is that a supernova does not return to its original state after the outburst; it has blown away so much of its material that it can never be the same again. In fact, a star can become a supernova only once, after which it sinks into a permanent decline.

Nobody knows the exact cause of these cosmic disasters, but the basic cause may be linked with the exhaustion of the hydrogen 'fuel' which has kept the star radiating for many millions of years previously. Some astronomers think that what we see is the abrupt transformation of a Red Giant into a White Dwarf. This may or may not be so, and all we can say is that events inside the star are responsible for the outburst.

In general, everything in the universe happens with majestic slowness, but this does not apply to the novæ and supernovæ. Developments take place so rapidly that we find it hard to keep pace with them; a formerly obscure star swells, flaring up into a veritable celestial searchlight, its spectrum changing constantly and its energy and material pouring away into space. It is a reminder to us that the heavens are not static, as the ancients believed, and that we are able to watch spectacles infinitely more dramatic than anything which can happen on our tiny Earth.

12

Clusters of Stars

If you look into the eastern sky during any evening in early autumn, you will see what appears to be a patch of shining haze. Look more closely, and you will see at once that the patch is really made up of stars, crowded close together so that they seem to be almost touching. If the sky is reasonably dark and clear, you will be able to make out at least six members of the group; keen-eyed people can distinguish a dozen, and binoculars reveal many more. The group is known officially as the Pleiades cluster, though the popular term for it is 'the Seven Sisters'.

The cluster lies in Taurus, the Bull, and is very easy to locate, since the line from Orion's belt through Aldebaran shows the way

FIG. 30. The Pleiades. A chart showing the positions of the nine stars which have been given proper names. Alcyone is the brightest of them (magnitude 3), followed by Electra and Atlas.

to it. Actually there is no need for an exact pointer, since the Sisters are so striking that they will be recognized without any difficulty.

It might be thought that the grouping is accidental, but analysis proves that any such chance lining-up of even half a dozen stars is out of the question. The odds against any such thing are so heavy that we may neglect them, particularly as telescopes show a grand total of something like 200 stars. The Pleiades members make up a true cluster, even though they are not nearly so crowded together as they seem.

There are many ancient legends about the Pleiades. One version tells us that they were seven nymphs, who were strolling placidly through a forest when they were pursued by the hunter Orion. Orion was attracted by their great beauty, and it is reasonable to assume that his intentions were anything but honourable; but just as he was about to overtake them, Jupiter changed them into doves and transferred them to the safety of the sky.*

The brightest Sister is Alcyone, of the 3rd magnitude. The rather less conspicuous Merope, Maia, Taygete, Electra and Atlas are also easy to see without optical aid. We therefore have six naked-eye Pleiads, and it is not easy to see why the cluster has always been known as the *seven* sisters, but there are suggestions that the peculiar shell-star Pleione, which is also a member of the group, used to be brighter than it is now. Actually it is visible now with the unaided eye on a clear night, and so are two more members of the group, Celæno and Asterope. Most people can see several other Pleiads as well, and the record is said to be held by a last-century German astronomer named Heis, who could count nineteen when the sky was really transparent.

The Pleiades seem so lovely in binoculars that they tend to be something of a telescopic disappointment. The area covered by the cluster is relatively large, and if you use a high power you will see only a small part of the group at any one time, so that the beauty is lost. On the whole, the best way to see the Sisters in their full glory is to view them through the lowest magnification available.

The distance of the cluster is somewhat uncertain, but exceeds 200 light-years; the diameter of the entire group is about 15 light-years, according to one recent estimate, so that the stars are not closely packed. Hundreds of similar 'open clusters' are known, and though the Pleiades hold pride of place there are several more which can be seen without a telescope.

Look for instance at the Hyades, which also are to be found in Taurus. They lie round the brilliant K-type star Aldebaran, and are just as easy to locate as the Pleiades, though they are not so striking. They are decidedly overpowered by Aldebaran's strong orange

* Fortunately, perhaps, the old legends tell us nothing about Orion's views on the matter.

light, and in some ways this is a pity, since Aldebaran itself is not a true member of the cluster at all. Here we have a genuine line-of-sight effect; Aldebaran lies roughly half-way between the cluster and ourselves. When you look for the rather V-shaped appearance of the Hyades, it is worth remembering that Aldebaran is as far from the cluster as we are from Aldebaran.

The Hyades, like the Pleiades, number about 200 stars, but they are more scattered. Moreover there are fundamental differences between the two clusters. In the Pleiades, the most luminous stars are blue giants with early-type spectra, mainly of type B, but in the Hyades we find that the leaders are red giants. Of course,

FIG. 31. The Hyades; a chart showing the leading stars. Rather unfortunately, the cluster is somewhat overpowered by the bright orange light of Aldebaran, which is not a genuine Hyad at all, and lies roughly half-way between the cluster and ourselves. For instance, Aldebaran is as far from ε Tauri as we are from Aldebaran.

this is not to say that all the Hyads are red giants—far from it—but the very brilliant blue stars characteristic of the Pleiades are absent, so that evidently the cluster is at a different stage in its evolution.

The proper motions of the Hyades stars can be measured, and an interesting fact emerges. All of them seem to be converging toward a point in the sky about five degrees to the east of Betelgeux. Here we have a perspective effect; the stars are not really closing in on each other, but are moving through space in paths which are virtually parallel. Aldebaran, on the other hand, is moving almost at right angles, so that in the distant future it will no longer masquerade as a member of the cluster.

Incidentally, the Hyades are receding from us, so that in time they will seem to shrink into a smaller, more compact group invisible without a telescope. However, these changes are so slow that delicate instruments are needed to measure them at all, and

Newton, Ptolemy and the builders of the Pyramids saw the cluster in the same form that we know today.

The third of the famous naked-eye open clusters is Præsepe in Cancer, popularly known as the Beehive. Cancer itself is distinguished as being in the Zodiac, but it is decidedly obscure, and contains no stars much brighter than the 4th magnitude; it looks not unlike a very dim and ghostly Orion. Fortunately it is easy to find, since it lies between the Twins, Castor and Pollux, and the Sickle of Leo. (Here too we have a legend, according to which Cancer was a sea-crab which attacked the hero Hercules as he was

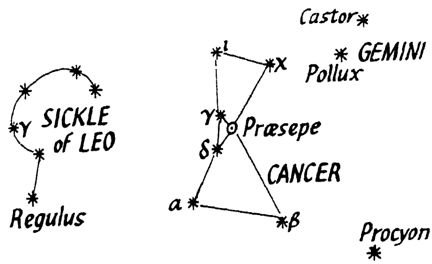


FIG. 32. Position of Præsepe. The cluster lies close to γ and δ Cancri, roughly in the middle of the triangle formed by imaginary lines joining Regulus, Procyon, and Castor.

battling with a particularly peevish monster. Hercules not unnaturally trod on it, but domestic quarrels among the Olympians led to its being transferred to the sky.) Præsepe lies near the middle of the constellation, and on a clear night it may be seen as a misty glow, though moonlight overpowers it. A low power on any small telescope shows it well, and according to one estimate it contains some 580 stars.

Southern observers enjoy the spectacle of another glorious cluster, surrounding the red star Kappa Crucis and nicknamed the Jewel Box. I have never seen it, but all descriptions agree in making it one of the loveliest objects in the stellar heavens. It lies in the Southern Cross, close to the 1st-magnitude star Beta Crucis.

Fainter but even more beautiful telescopically are the twin clusters in Perseus, marking the sword-handle. The best guide here is Cassiopeia, since two of the stars in the W point toward it. It is just visible to the naked eye, and in a telescope is revealed as not one object, but two—similar clusters in the same low-power field. This is not a line-of-sight effect, since the clusters are true neighbours.

The twins are very remote. They are indeed so far away that their distance is uncertain, but 4000 to 5000 light-years is a reasonable estimate, which means that the brightest members must be up to 100,000 times as luminous as the Sun. Vast red supergiants are also to be found, and in general the hot early-type stars form the nuclei of the clusters with an aura of red supergiants beyond. It is a great pity that the twin system is so distant; if the clusters were nearer, they would provide a spectacle beside which the Pleiades would pale into insignificance.

A list of fainter clusters worth looking for with a small telescope is given in the Appendix, and it will be seen that most of the objects are given 'M' numbers. These refer to a catalogue drawn up in 1781 by the French astronomer Charles Messier, and which is still used, though since then many more detailed catalogues have been compiled. Ironically enough, Messier was not particularly interested in clusters. His main concern was in hunting for comets, and he found that he was apt to be deceived by clusters and nebulæ, which often look rather like telescopic comets. To avoid wasting time, Messier made a list of the clusters and nebulæ so that he could identify them without laborious checking. Nowadays Messier's comets are forgotten by all but a comparatively small band of enthusiasts, but his catalogue has made his name immortal. The Pleiades are listed as M.45; Præsepe, M.44, and so on. Oddly enough Messier did not include the Perseus sword-handle, and of course southern objects such as Kappa Crucis never rose above the horizon in France, where he carried out all his observational work.

Messier could—and did—list many of the open clusters, but he had no means of telling of the existence of 'moving clusters', which do not show up as compact groups. The best example of such a moving cluster is the Plough. Of the seven famous stars, five are found to be moving through space in the same direction at about the same rate, so that they will keep the same relative positions for a long time even on the cosmic scale. In the distant future, these five stars will still form the pattern which we know today, whereas the two remaining Plough stars—Alkaid and Dubhe—will not.

A moving cluster of this sort may be a relation of a more conventional open cluster, but occupies a larger volume of space, and in general contains fewer members. Moreover, non-cluster stars may penetrate it and move through it. The stars in a moving cluster do not affect each other appreciably, since they are far apart, and so the cluster will not be permanent; the present arrangement shows that the member stars must be rather young, and the cluster has not had enough time to disperse.

Another moving cluster is made up of a very spread-out group of O and B stars in the region of Scorpio and Centaurus, while even more interesting is the system of very hot early-type stars near the supergiant Zeta Persei. Here we have over fifteen stars, moving in a way which suggests expansion from a definite centre; the rate of expansion is about 8 miles per second, and it has been calculated that the expansion began about 1,300,000 years ago. The inference is that this is also the age of the stars concerned—which is reasonable, since all show O or B spectra, and must be young stars squandering their energy at a prodigious rate.

Groups of this sort are obviously important, because they can tell us a great deal about the past careers of the member stars. Astronomers all over the world are busy studying them, particularly the Americans and the Russians. Co-operative work of this kind shows that astronomy is a truly international subject, as all sciences should be.

Let us now turn from the moving clusters, which are scattered so widely that they cannot be recognized on sight, to the globulars, which are as different as they can be. The two most spectacular examples lie in the southern part of the sky, and are consequently never seen in Britain. One is Omega Centauri; it was lettered by Bayer, who apparently regarded it as some sort of star. The other is 47 Tucanæ, in the rather faint constellation of the Toucan. Each is visible to the naked eye, and in a telescope each is revealed as a superb 'ball' of stars, strongly condensed toward the centre.

In the northern hemisphere, the brightest globular cluster is M.13 Herculis. It is just visible without optical aid, but is none too easy to find unless its position is known accurately, particularly as Hercules itself is not brilliant. The cluster lies between Zeta and Eta Herculis, rather nearer to Eta. If you cannot see it with the unaided eye, the best course is to use a low power on your telescope and sweep from Zeta toward Eta; you should then find the cluster without much trouble. Small instruments show it as a dim patch, but with a moderate telescope it is a fine sight, and my own 12½-inch reflector shows its starry nature well.

Globular clusters are comparatively rare. About a hundred are known, and the whole Galaxy contains probably at least double this

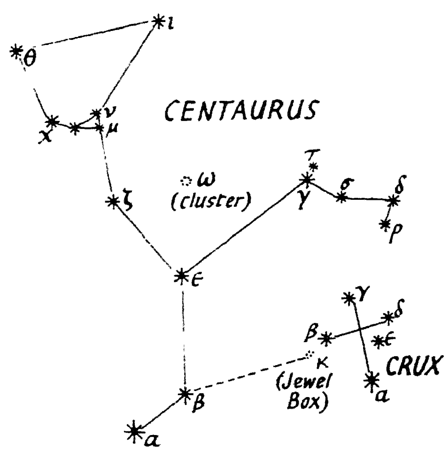


FIG. 33. Positions of two glorious southern clusters: the 'Jewel Box' round κ Crucis in the Southern Cross, and the globular ω Centauri. Northern observers bemoan the fact that neither cluster can be seen from the latitudes of Europe.

number—but the open clusters of the Pleiades type run into thousands. Moreover, most of the globulars are faint, and even Omega Centauri is not particularly striking without a telescope. This is not because the globulars are really dim, but because they are very remote. Omega Centauri, which is admittedly rather above the average, has a total luminosity of perhaps a million Suns, and lies at a distance of 22,000 light-years; M.13 Herculis is even farther away, since it is 34,000 light-years from us.

The distribution of the globulars is rather unexpected. They are not uniformly spread around the sky, and most of them are in the south, in the region of Scorpio and Sagittarius. As will be shown below, it was this apparently lop-sided distribution which led to the discovery that our Sun lies well out to the edge of the Galaxy instead of in the middle of it, as Herschel had believed. But the globulars are worth studying in themselves; each contains thousands of stars, and perhaps 100,000 is a fair average, though there is no general agreement among astronomers. No photograph can give a real impression of the glory of such a cluster, but it is easy to see that there is no prospect of counting each separate star, since toward the centre the individual points of light merge into a general blur.

Since the globulars are so remote, it is natural to ask how we can be so precise as to their distances—precise, that is to say, from the astronomer's viewpoint; there must be considerable uncertainty, as is always the case except with very nearby objects. The answer is that the globulars contain a good many RR Lyræ variables. As we have seen, the RR Lyræ stars are of roughly equal luminosity—90 times that of the Sun; if we measure their apparent magnitudes we can therefore work out their distances, and they act as first-class standards of reference.

An everyday comparison will show what is meant. If you are standing on the sea coast, and see a light across the water, you have no immediate way of telling whether it is a faint lamp close at hand, or a powerful light a long way away; but if you know its real luminosity, its distance can be estimated with some accuracy. The RR Lyræ stars therefore come in remarkably useful. Originally they were thought to be peculiar to clusters, and were known as cluster variables or cluster-Cepheids; but it is now known that many of them—including RR Lyræ itself—are not members of clusters, and neither are they true Cepheids, though it is fair to say that they are relations of the classical Cepheid stars.

One other fact is worth bringing out. In the globulars, the brightest and therefore most powerful stars are red supergiants, with vast diameters but relatively low surface temperatures of a few thousands of degrees. (A few globulars contain hot blue stars as well, but these are decidedly exceptional.) Therefore, the globulars seem to be made of stars which are well advanced in their life-stories, though we must remember that the great distances involved mean that we cannot hope to obtain a complete picture. Relatively feeble stars of the same brightness as the Sun cannot be made out at all, and we can study only the more luminous members of the systems.

The central condensations are real, and near the middle of a globular the average distance between individual stars is much less than in our part of the Galaxy. The actual distances are still very great, and collisions must be excessively rare, but any one star is almost bound to have several more within a couple of light-years of it. Moreover, many of these would be very luminous, whereas our nearest neighbour, Proxima Centauri, is a dim Red Dwarf. Suppose that we can take a trip to a planet revolving round one of the stars near the middle of the Omega Centauri globular? What sort of sky will we see, and will it be very different from the star-studded vault which we know?

Undoubtedly the scene will be magnificent. Instead of a few brilliant stars there will be many thousands; probably at least thirty will shine more brilliantly than Venus does to us, and it is quite on the cards that one or two will rival our Moon, so that instead of appearing as twinkling points they will show real disks. There is also a strong chance that they will be red, since—as we have seen—the most prominent members of the cluster are red supergiants. Even if we assume that our hypothetical planet spins on its axis in much the same time as the Earth, there will be no true night. The glare of the stars will provide much more light than our full moon, and very dark nights will be unknown.

If we go a step further, and suppose that our planet is inhabited by a race of beings who share our own interest in the universe, we can see that certain difficulties will have to be faced. Admittedly the relatively close stars will be well displayed, but fainter objects will be drowned in the general glare, so that it will be impossible to study objects beyond the confines of the cluster.

The proper motions of the stars will be more apparent than is the case with us, since the stars in a globular are moving in orbits round the centre of gravity of the system, and even over comparatively short periods these shifts will become marked. No constellation will keep its outlines permanently, and star-maps will have to be re-drawn every few centuries. In addition, the apparent magnitudes of the stars will change. A red supergiant which passes within a light-year of our imaginary planet will dominate the night sky; as it passes its nearest point of approach and begins to recede once more, its disk will shrink and its glare dwindle into a soft glow. There is also the point that supergiants run through their life-stories more quickly than placid stars such as the Sun, and it is likely that magnitude changes would be caused on this account as well. No narrow-minded astronomer living in a globular cluster would be able to maintain that the skies are unchanging, as our own philosophers believed only a few thousands of years ago.

It is interesting to speculate as to the theories which might be held by cluster-dwellers. Probably they would imagine their own star-system to be the only one, and they might well believe that the universe is very limited in extent. They might have shrewd suspicions that other systems lie beyond their local globular, but proof would be very hard to obtain.

Of course, we have no idea whether there are any planetary families inside the Omega Centauri cluster or any other globular, but there is no obvious reason why such families should not exist. Each globular contains tens of thousands of stars, and it is reasonable to suppose that there are many cluster-suns with Solar Systems similar to ours. Unfortunately there is at present no hope of finding out for certain one way or the other.

We can see that there are associations and groups of all kinds, from the spread-out moving clusters to the open clusters such as the Pleiades, the more complex systems such as the Perseus sword-handle, and the wonderful starry spheres which are the globulars. There is endless variety in the stellar universe.

13

Nebulæ

Whenever the sky is dark and clear, and Orion is above the horizon, the unmistakable pattern catches the eye at once. There can be few people who do not know the three bright stars which make up the Belt, and close by is the Hunter's Sword, which looks rather like a faint patch of milky fog. Moonlight drowns it, but under good conditions it is easily visible without a telescope. It is the brightest of the objects which we call gaseous nebulæ, and has been known for centuries. Astronomical names are often inappropriate—we need think only of the lunar 'seas' which contain no water, or the Martian 'canals' which are certainly not artificial—but in the case of Orion's Sword, the term nebula, or cloud, seems apt enough. A layman might well be forgiven for mistaking it for a tiny patch of cloud still catching the rays of the Sun.

With a small instrument such as a 3-inch refractor, the Orion Nebula is a lovely sight. In its midst appears the famous multiple star Theta Orionis, the famous Trapezium, and there are other stars too, most of which are really mixed in with the nebula. The general impression is that the stars are lighting up the cloud and making it shine, though as a matter of fact this is only part of the story.

Equally famous is the dim, misty patch popularly called the Great Nebula in Andromeda, which is not hard to see with the naked eye on a clear night. Originally it was thought to be of the same type as the Sword of Orion, which is why both were termed nebulæ, but as equipment became more powerful there were suggestions that the two objects were not really alike. When Sir William Herschel carried out his reviews of the sky more than a century and a half ago, he realized that while some nebulæ could be resolved into stars, others could not. In particular the Andromeda Nebula was resolvable, at least in its outer parts, whereas the Sword of Orion showed no stellar structure at all.

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The first mention of a nebula goes back to the tenth century, when the Persian astronomer Al-Sûfi recorded the object in Andromeda. It was then more or less forgotten until Simon Marius, an enthusiastic and skilful German observer, mentioned it again in 1612; about the same time N. Peiresc gave the first description of the Sword of Orion. As time went by, more and more objects became known, and—as we have seen—Messier catalogued over a hundred of them, simply because he was constantly annoyed by them during his painstaking searches for comets. But Herschel carried matters much further, and in 1786 he published a catalogue containing more than a thousand clusters, resolvable nebulæ and irresolvable nebulæ.

At first Herschel seems to have been unsure whether or not he could draw a real distinction between the two types of nebulæ, though he certainly mentioned 'nebulosity of a milky kind' near Theta Orionis. Later, in 1791, his ideas became more definite, and he wrote: 'Our judgment, I venture to say, will be that the nebulosity about the star is not of a starry nature.' He wondered whether space might contain some sort of shining fluid, and he added that this self-shining matter 'seemed more fit to produce a star by its condensation, than to depend on the star for its existence'. Herschel was certainly far-sighted; here we have the modern view of stellar birth, a hundred years before it could be drawn up into a firm theory.

Alone, the telescope could give no answer to the problem of the two kinds of nebulæ, but the development of the spectroscope opened up whole new avenues of research. The decisive experiment came on August 29, 1864, when Sir William Huggins, pioneer of stellar spectroscopy, began to study the spectra of nebulæ as well.

We know that a normal star yields a rainbow background crossed by dark absorption lines. If therefore a nebula is made up of stars, the result will be a jumble of all the separate spectra put together; early-type stars, late-type stars, giants, supergiants and dwarfs. It is reasonable to hope that the main dark lines will be recognizable, and there should certainly be a continuous background. When Huggins turned his spectroscope toward an 'irresolvable' nebula in Draco, he found that this was by no means the effect which he saw. Bright emission lines appeared, and not many even of these.

Huggins realized at once that there could be only one explanation; instead of being stellar in nature, the nebula was composed of shining gas.

Herschel had been right. There is a vital difference between the two types, and we now know that the resolvable nebulæ are stellar systems in their own right, far beyond the boundaries of our own. They have been re-named 'galaxies', and it is misleading to call them nebulæ at all. Objects such as the Sword of Orion are known as gaseous or galactic nebulæ.

The Orion Nebula—No. 42 in Messier's catalogue—may be minor compared with a galaxy, but it is extremely large judged by our local standards. If we agree that its distance is 1000 light-years, which seems to be reasonable, its diameter must be at least 20 light-years.* On the other hand the density is incredibly low, and is equivalent to what we generally term a vacuum.

The fact that M.42 yields a bright-line spectrum shows that the gas must be self-luminous, and is not merely reflecting the light of the stars contained in it. However, these stars are directly responsible. They are very hot objects of types O and B, and it is the ultra-violet radiation sent out by them which affects the nebular gas and excites it to luminosity.

Hydrogen is by far the most plentiful substance in the universe, and so it comes as no surprise to find that galactic nebulæ consist largely of it. Other elements such as oxygen and helium also occur, and there are prominent spectrum lines which are still known as 'nebulium' lines. When first found, these lines caused a great deal of interest, because they did not correspond with any substance which could be produced in the laboratory, and it was thought that they must be due to a completely new element—hence the name Nebulium. There was a strong precedent, since helium had first been identified in the spectrum of the Sun and had not been found on our world until a quarter of a century later. Nebulium remained a mystery until 1927, but then an American astronomer, I. S. Bowen, proved that it was due to nothing more fundamental than common elements (mainly oxygen and nitrogen) in unfamiliar

* This value is for the part of the nebula which is shining brightly enough to be seen. The actual extent of the complete gas-cloud is probably much greater.

states. It was something of an anti-climax, but at least it was satisfying to solve the puzzle.

When discussing stellar evolution we saw that galactic nebulæ might well be the birthplaces of the stars. It is true to say that much of our information has been drawn from the Sword of Orion—not because it is unusual, but because it is comparatively bright and easy to study. In particular, it contains over 200 irregular variables which are probably among the youngest stars known. The first of them, AF Orionis, was detected as long ago as 1848, but nowadays the stars are known as T Tauri type variables, after another member of the class which will be described below. It is thought that the light fluctuations are due, in some way, to the stars' extreme youth. As the years pass by in their millions, the T Tauri variables will presumably settle down into normal stars shining steadily and respectably.

Recently some fascinating work has been carried out in America by two astronomers named Blaauw and Morgan. Their attention was drawn to a faint O-type star, AE Aurigæ, which seems to have a remarkably high velocity of something like 80 miles per second. It seems faint only because it is so far off, and since it is decidedly energetic on the stellar scale it is almost certainly young. If we trace its path backwards, we find that about 2,600,000 years ago—when our world was still in the Pliocene period, and men still lay in the future—AE Aurigæ must have been in the region of the Orion Nebula. In almost exactly the opposite direction we find another O-type star, Mu Columbæ, with a similar velocity but moving the other way; it too must have been in the Orion Nebula region 2,600,000 years ago. The suggestion is that some colossal disturbance took place at about that time, hurling AE Aurigæ and Mu Columbæ violently in opposite directions. To this we may add a third star, 53 Arietis; the agreement is not so good, but lies within the limits of observational and theoretical uncertainty.

We may make some guesses as to what happened. All three stars are infants on the cosmic scale, and presumably they are of the same age. Can it be that they were once near neighbours—perhaps at that stage in their careers when they were still, broadly speaking, 'being formed'—and that some outburst sent them on their different courses, so that by now they are so far apart that as seen from

Earth one lies in Columba, one in Auriga and one in Aries? It is at least possible. The full answer is not yet known, and we cannot tell why three such stars should have been ejected with such incredible violence, but there are strong reasons for thinking that we are at least on the right track.

T Tauri itself, the prototype of the irregular variables such as those found in the Orion Nebula, is a most extraordinary object, and is concerned in what might be known as 'the Case of the Vanishing Nebula'. The nebula itself lies near the Hyades, well away from Orion's Sword, and was first noticed in 1852 by John Russell Hind, an observer who was particularly interested in minor planets and was searching for them with the help of a 7-inch refractor. He described it as 'a very small nebulous-looking object' close to a 10th magnitude star. T Tauri, the star concerned, was a variable, but Hind naturally did not realize that there was anything peculiar about it.

The nebula was duly listed, and seemed to be perfectly normal, but in 1861 a German astronomer, Heinrich d'Arrest, found to his amazement that it had almost disappeared. Very large telescopes still showed traces of it, but by 1868 it had completely gone. Hind's nebula was officially regarded as 'missing', but other developments were taking place nearby. In 1868 Otto Struve found nebulosity round a 14th magnitude star close to T Tauri, and d'Arrest, who had previously looked closely at the area, was certain that the nebulosity was new. It was recorded at various times until 1877, but has never been seen since.

Then in 1890, Barnard and Burnham, using the 36-inch Lick refractor, rediscovered Hind's old nebula. It was visible, but a mere ghost of its former self, and was a difficult object even with this vast telescope. Late in 1895 it vanished again, to reappear once more later on. Nowadays it is easily visible with large instruments, but its form is not the same as when Hind first reported it. Of course, it is not in Messier's list; its official designation is N.G.C. (= New General Catalogue) 1555.

To make matters even more complex, T Tauri itself is embedded in nebulosity—and this nebulosity also is variable. And as a last puzzle, it has been found that Hind's nebula yields emission lines, though T Tauri is a yellow dwarf not nearly hot enough to excite nebular gas to luminosity. Altogether, we must agree that this is one of the most baffling areas in the sky.

It is tempting to suggest that the hide-and-seek behaviour of Hind's nebula is due to changes in brilliancy of T Tauri, but some authorities doubt this, since the nebula is much more variable than the star. It has been suggested that changes in illumination are more largely responsible, so that whereas in Hind's day the gas was brightly lit by the star, some other material moved in around 1860 and cast what is to all intents and purposes a shadow; but nobody really knows.

All we can say is that T Tauri is closely associated with the nebula, and was possibly born out of it. A similar process is going in the Sword of Orion, and it has been suggested that two stars photographed there in 1954 did not exist in such a form in 1947, but we must be very wary of jumping to conclusions.

Hind's object is not the only variable nebula known. Others are associated with the irregular variables R Monocerotis, in the Orion area, and R Coronæ Australis in the southern sky. Unfortunately all these nebulæ are so faint that large telescopes are needed to show them, and almost all research is carried out photographically.

A nebula does not consist exclusively of gas. 'Dust' is present as well, though the proportion seems to vary from nebula to nebula. If there are no sufficiently hot stars available, the ultra-violet light is not enough to make the gas self-luminous, and so the nebulosity shines only by reflection, as in the case of the faint nebula mixed in with the Pleiades. In general, we may say that unless a star has a surface temperature of about 18,000 degrees it is unable to make a nebula shine on its own, and the Pleiades stars, while hot, are not so hot as this.

M.8, the Lagoon Nebula near the 4th magnitude star Mu Sagittarii, is another galactic nebula well seen in a small telescope; also in Sagittarius is M.17, the Omega or Horseshoe Nebula, while southern observers have the Keyhole Nebula, which surrounds the extraordinary variable Eta Argûs and is said to rival the Sword of Orion.

We have seen that nebulæ associated with very hot early-type stars become self-luminous, while if the nearby stars are cooler the nebula is visible by reflection. Suppose that there are no convenient stars close enough to provide these reflection effects? Presumably the nebula will remain dark—and this is exactly what we find.

A dark nebula can be detected because it cuts out the light of stars lying beyond, just as a cloud of smoke will obscure a distant street lamp, and the outlines of the nebula will be clearly traceable. For once Herschel made a mistake here; it is said that on coming across one of these patches during a sky-sweep, he exclaimed 'This, surely, is a hole in the heavens!' Yet there is no chance of stars

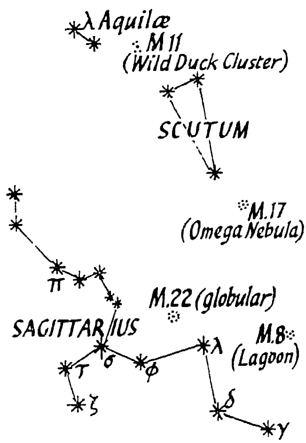

FIG. 34. Sagittarius; a region very rich in clusters. The four shown here are M.8 (the Lagoon Nebula), M.17 (the Omega or Horseshoe Nebula) and M.22 (a globular cluster) all in Sagittarius, and M.11 (the Wild Duck cluster) in Scutum, not far from Lambda Aquilæ. An imaginary line from Deneb passed through Altair and extended to the south will indicate the general direction of Sagittarius. The constellation is bright, but contains no 1st-magnitude stars, and there is no really distinctive shape; moreover observers in Britain never see it to advantage, as it is always low.

being absent in one particular direction, and so the only logical explanation is a shielding nebula.

The best of these dark clouds lies in the Southern Cross, and is thus never visible from Britain. It is known as the Coal Sack, and blots out an area of sky 8 degrees long by 5 degrees wide. As a matter of fact it is not completely opaque; but it is very noticeable, and there is nothing so striking in the northern hemisphere, though smaller obscuring clouds are to be found in Cygnus and elsewhere.

Near the star Rho Ophiuchi, bright and dark nebulæ appear close together in the sky, giving a wonderful effect.

There is no basic difference between a bright nebula and a dark one; it all depends on whether there are suitable stars either to make the nebula luminous or to provide it with reflected light. Astronomers believe the obscuration to be due mainly to fine 'dust', and we do at least know that the Galaxy is a decidedly dusty place.

The distances of dark nebulæ may be found by various indirect methods, and the Coal Sack proves to be about 400 light-years away, which means that it must be something like 40 light-years across. If our Sun lay near the centre of a comparable cloud, familiar stars such as Alpha Centauri, Procyon, Sirius and Altair would also be enveloped in it.

The general question of cosmic dust is best left until we come to discuss the Galaxy as a whole. First, let us pay some attention to various objects which are often classed with the nebulæ, though strictly speaking they are not nebulæ at all.

The extraordinary object known as the Crab Nebula is of particular interest, because we know a great deal about its past history. It lies near the 3rd-magnitude star Zeta Tauri, and a small telescope will show it, though it is not really prominent; to study its delicate structure, photographs taken with large instruments are needed. It is the wreck of the supernova of 1054, and even now the gas is still expanding outward from the site of the explosion. There is a faint star near the centre which seems to be a White Dwarf, though it is of unusual type and may not be like the White Dwarfs nearer home.

The total mass of the nebula has been estimated about 15 times that of the Sun. It is logical to suppose that before the outburst, all this material was contained in the original star; and since a star 15 times as massive as the Sun is a celestial heavyweight, the pre-supernova star must have been a giant. Astronomers would very much like to know whether or not it used to be a Red Giant, but probably we shall never find out, and it may be centuries before another supernova bursts forth in our Galaxy. At any rate, it is a sobering thought that we can still see the results of a stellar catastrophe which was watched by our ancestors more than 900 years ago. At its maximum, the Crab star must have shone 10 million times as brightly as the Sun.

If you have a telescope of moderate power, look closely at a point midway between Beta and Gamma Lyræ, close to the brilliant Vega. The two are easy to find; Beta is the celebrated eclipsing variable, while Gamma is a normal star of the 3rd magnitude. In the mid position you should be able to make out a dim patch, and increased power will show it as a luminous ring, not unlike a tiny shining bicycle tyre. This is the best example of a class of objects known as planetary nebulæ. The name could hardly be more ill-chosen, since the objects are neither nebulæ nor planets; they are in fact stars with tremendous, rarefied 'atmospheres' of gas. Actually the name is due to Herschel, who once thought it possible that the objects might be planetary systems circling other stars, though later on he realized that this could not be the case.

The Ring Nebula in Lyra, No. 57 in Messier's catalogue, is not really tyre-shaped, since presumably there is a uniform shell of gas round the faint central star. The diameter is rather less than 1 light-year, but other planetaries are larger. N.G.C. 7293 in Aquarius, which is fairly typical, is roughly twice the size of the Ring Nebula. If the Sun were to lie on one edge of a planetary of such dimensions, the opposite edge would extend well out toward Alpha Centauri.

Yet the planetaries are not nearly so massive as might be thought from their vast size, and this, of course, is because they are so tenuous. If it were possible to take a cupful of air and spread it around a giant vacuum-flask 5 miles in diameter, the resulting density would be roughly that of the gas in an average planetary nebula. On the other hand the central stars are of the White Dwarf type, and are immensely heavy.

It is easy to draw a comparison between planetary nebulæ and shell stars of the Wolf-Rayet type, and there may be a real relationship. This idea is strengthened by the fact that the shells of planetaries seem to be spreading outward at speeds of up to 30 miles per second, and it has even been suggested that a planetary nebula is the result of a former nova explosion. It would be fascinating to look into the future and see whether objects such as RR Pictoris and DQ Herculis end up by turning into planetaries; but of course the process, even if valid, must take a very long time indeed.

About 500 planetaries are known, but most of them are beyond the reach of small telescopes. Not all are symmetrical; the Dumb-bell Nebula in Vulpecula, not far from Gamma Sagittæ in the neighbouring constellation, lives up to its name, and the Owl Nebula in Ursa Major, not far from Merak (the fainter of the two Pointers) also has a distinctive shape. A planetary worth looking for with a small aperture is H.IV.I—not catalogued by Messier —which is easy to find, as it lies in the same low-power field with the orange star Nu Aquarii. In very large instruments it is seen to show extensions which remind one of Saturn's ring system.

Astronomy has made great strides since Messier drew up his catalogue of 'objects to avoid' during searches for comets. The so-called nebular objects are by no means all alike; some are bright and some dark, some shine by themselves while others depend upon reflected glory, and some are variable, while yet others are stellar wrecks or exceptional shell-stars. But of all these, it is perhaps the ordinary gas and dust clouds which hold the greatest fascination for us, for here it seems that new suns are being created. Thousands of millions of years ago, our own Sun was born in the same way.

14

The Galaxy

On a summer night, when the Sun has set and the stars are glowing brilliantly, one of the most wonderful sights in the heavens is the Milky Way. It stretches across the sky, making up a band of radiance which cannot be mistaken. As Ptolemy wrote in his *Almagest*, 'The Milky Way is not a circle, but a zone, which is almost everywhere as white as milk, and this has given it the name it bears. Now, this zone is neither equal nor regular everywhere, but varies as much in width as in shade of colour, as well as in the number of stars in its parts, and by the diversity of its positions; and also because that in some places it is divided into two branches, as is easy to see if we examine it with a little attention.'

Ptolemy's account dates back nearly 2000 years, but as a description of the Milky Way as seen with the naked eye it could hardly be bettered. If we start by looking at the luminous zone as it appears in Cassiopeia, we can follow it through Perseus, Auriga, Gemini, past Procyon and Sirius down to the southern horizon as seen from Britain; it then crosses Argo, the Southern Cross and Centaurus, and thence into Scorpio and Sagittarius, Aquila, Cygnus and back to Cassiopeia. The section between Argo and Sagittarius never rises above our horizon, and this is unfortunate, since it is a particularly rich zone; in Crux, moreover, we have the celebrated dark Coal Sack. However, the most brilliant part of the whole Milky Way is in Sagittarius. This is within range of British observers, though it is always rather low down in the sky; it is best seen during summer evenings, when it is in the south.

The Milky Way must have been known from very early times, and our remote ancestors, half-man and half-ape, undoubtedly looked up at it and wondered what it was. In Greek times various theories were put forward, some of them more logical than others. Parmenides of Elea, who lived toward the end of the sixth century

B.C., held that 'it is the mixture of the dense and the rarefied which produces the colour of the Milky Way'. (To do him justice, he also stated that the stars were made of 'compressed fire', so that at least he knew them to be self-luminous.) Anaxagoras of Clazomenæ, born about 500 B.C., believed that 'the Milky Way is the light of certain stars. For, when the Sun is passing below the Earth, some of the stars are not within its vision. Such stars, then, as are embraced in its view are not seen to give light, for they are overpowered by the rays of the Sun; such of the stars however as are hidden by the Earth, so that they are not seen by the Sun, form, by their own proper light, the Milky Way.' This may seem rather involved; Anaxagoras, of course, believed the Earth to be flat, while to him the Sun was a large red-hot stone. On the other hand he knew that the Milky Way is made up of stars, and is not anything in the nature of a shining fluid.

When Galileo first began to use the telescope as an astronomical tool, in the winter of 1609-10, he naturally looked at the Milky Way, and what he saw fully confirmed Anaxagoras' view. Galileo wrote that 'the Galaxy is nothing else but a mass of innumerable stars planted together in clusters. Upon whichever part of it you direct the telescope, straightway a vast crowd of stars presents itself to view; many of them are tolerably large and extremely bright, but the number of smaller ones is quite beyond determination.'

Here again we have a description which might well have been written by any modern astronomer. The greater the light-gathering power of your telescope, the more stars you will see; but even a 3-inch refractor used with a low magnification gives superb views of the rich star-fields, and to count each separate star would be impossible even with the help of photographs. It seems as though the stars are crowded so thickly together that there is almost no spare room between them.

Nothing could be further from the truth. The stars of the Milky Way are not crammed together, and once more we are faced with a line of sight effect. Once again, too, we come back to the work of Sir William Herschel, who was the first astronomer to put forward a really sound scheme for the arrangement of the stars, though admittedly one or two earlier theorists had been more or less on the right track.

Herschel knew that he had no hope of counting all the stars, so he decided to count the stars in certain selected regions in the sky. This was the famous 'star-gauging' method, and Herschel worked away at it for many years. His final conclusions were not fully accurate, but were vastly better than any which had been drawn before.

Herschel believed (wrongly) that the apparent brightness of a star must be a reliable guide to its distance from us, so that brilliant stars such as Sirius, Canopus, and Rigel were closer than fainter ones such as Polaris. This would be valid if the stars were even roughly equal in luminosity, but in practice it does not fit the facts, and it is worth noting that Canopus and Rigel, which are among the ten apparently brightest stars in the sky, are exceptionally powerful and very remote. Herschel cannot be blamed for falling into this trap, and indeed he had no means of knowing better. He also thought that the regions of the sky which contained the most stars represented the greatest extensions of the stellar system—and this was where his star-gauging method came in. Of course there are more stars in and near the Milky Way than in other regions of the sky, but Herschel soon found that the percentage increase was greater for faint stars.

For instance, suppose that we take two telescopes, a 3-inch refractor and a 15-inch refractor, and use them to examine a selected area near the Milky Way as well as another area in one of the most barren regions of the heavens—such as the constellation Lynx, not far from Ursa Major—which will lie at the so-called 'galactic pole', as far as possible from the Milky Way. Our small telescope will show only bright objects, and it will be found that the rich region will contain about four times as many stars as the barren one. With the large telescope, which will show fainter stars as well, the ratio is bound to be much higher, probably about 10 to 1. In other words, faint stars are more numerous near the Milky Way than might be expected.

Herschel decided that the stellar system or Galaxy must be shaped rather like a double-convex lens, or two plates clapped together by their rims, as shown in the first diagram. This would explain the Milky Way effect. Assuming the Sun to lie near the middle of the system, large numbers of stars would be seen in directions SA and SB, giving rise to the luminous band; relatively few stars would lie at right angles (SC and SD), which would account for the barren areas near Lynx and its southern counterpart, Sculptor. Herschel had no means of finding out the real dimensions of the system, since in his day star distances were unknown, but he could at least give a general picture of the shape of the Galaxy. He himself described it as resembling a 'cloven grindstone'.

Nowadays we know that a great many of Herschel's ideas were correct. It was an amazing achievement on his part, particularly when we remember that he had to work out his own methods and even build his own telescopes.

Little more was done for half a century following Herschel's death, but at last, in 1904, the Dutch astronomer Jacobus Kapteyn

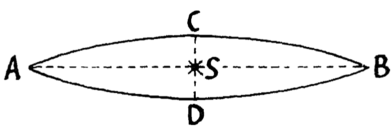

FIG. 35. Old idea of the shape of the Galaxy. S = the Sun; many stars would be seen in directions SA and SB, fewer in directions SC and SD.

showed that the proper motions of the stars are not entirely random; there is a tendency for a general drift in two special directions. Since all stellar proper motions are tiny judged by ordinary standards, the effects of star-streaming are very slight, but Kapteyn knew that the phenomenon was a real one. Accordingly he decided to attack the problem of star distribution rather along the lines laid down by Herschel, but fortunately he did not have to do all the work himself. Observatories all over the world co-operated in examining over 200 selected regions for star counts, and from the results Kapteyn was able to draw up a new picture of the Galaxy. Again the Sun, together with its family of planets, was assumed to be rather close to the centre of the system.

The idea of a centrally-placed Sun was reasonable enough. A fly sitting on the hub of a bicycle wheel will theoretically be able to see the rim both above, below, and to the right and left; similarly the Milky Way forms a complete band in the sky, and the fact that it is richer in some places than in others might be dismissed as mere coincidence. The key to the whole problem proved to be given by the globular clusters, as was shown by the work of Harlow Shapley at Harvard in the years immediately following the end of the First World War.

Globular clusters, as we have seen, are magnificent objects, but British observers never see the best of them to advantage, and in particular the brightest of all, Omega Centauri and 47 Tucanæ, lie so far south in the sky that in our latitudes they never rise at all. Shapley saw that not only were northern observers far worse off than their colleagues south of the equator, but that the grouping was too marked to be due to chance. Over 100 globulars are known, and most of them lie in the south, particularly towards the constellations of Scorpio and Sagittarius. This is not to say that globulars are absent from the northern skies; for instance, Messier listed one in Canes Venatici and another in Hercules (M.92), as well as the famous Hercules globular (M.13). Yet it is very obvious that the northern hemisphere is strangely bare of such objects. The odds against such a lop-sided distribution being due to coincidence are astronomical in every sense of the word, and Shapley ruled it out at once. There had to be some other explanation.

Shapley realized that the globulars form a kind of outer surround to the main Galaxy, and that they lie on the fringes of the whole system, which is why all of them are comparatively remote from us. Unfortunately their distances were hard to measure; older methods such as trigonometrical parallax were useless. It was at this point that the RR Lyræ stars came to the rescue.

Remember that RR Lyræ stars, variables of short period, are almost equal in luminosity, and shine about 90 times as brightly as the Sun. As soon as we can measure their apparent magnitude, therefore, we can find their distance. This is what Shapley did with the RR Lyræ stars inside globular clusters, and for the first time it became possible to work out the distances of the globulars themselves, which in turn led on to a much more reliable idea of the shape of the Galaxy.

The mystery of the lop-sided distribution was solved at once: the Solar System lies well away from the centre of the Galaxy, and so we have an unsymmetrical view. This is where Herschel had been utterly wrong, even though his 'cloven grindstone' scheme was not far from the truth.

Now we can draw up a proper picture. There is a central nucleus lying in the direction of the Sagittarius star-clouds, and the Galaxy has the flattened shape shown in the diagram; the system measures about 100,000 light-years from side to side, with the Sun 25,000 light-years from the centre. The thickness of the system is greatest at the centre, but a round figure to take would be 20,000 light-

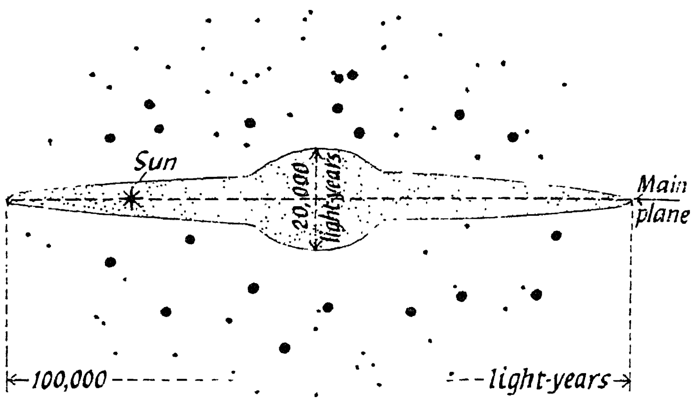

FIG. 36. Modern ideas of the shape of the Galaxy. The system measures 100,000 light-years from side to side, and is 20,000 light-years across the nucleus. The Sun lies well out toward one side. Surrounding the Galaxy is the galactic corona, consisting of stars and globular clusters—roughly 100 stars to each globular. In the diagram, which is merely intended to give a rough impression, stars in the galactic corona are drawn as small dots and globular clusters as large dots.

years.* Surrounding the main mass of stars is the galactic corona, a sort of outer skeleton of globular clusters and individual stars.

Faced with distances of such an order, stars such as Alpha Centauri or even Polaris seem very close neighbours indeed, and we can well understand why the parallax methods used by Bessel and his contemporaries broke down so hopelessly; no globular lies much within 20,000 light-years of us.

The short-period variables provided the essential clue, but there are many refinements to be taken into account, one of which con-

* These figures are certainly not wildly in error, but they are bound to be rather uncertain, and different authorities give different values.

cerns interstellar matter. The space between the stars is by no means empty; it contains obscuring material in the form of dust and gas, and stars whose light comes to us through such material are both dimmed and reddened, just as a car headlight is affected by smoke or mist. We are familiar enough with the bright and dark nebulæ, but it was not until the present century that we obtained definite proof of a more general obscuring haze. The star mainly responsible was Delta Orionis, the northern member of the Hunter's Belt.

Delta Orionis is a spectroscopic binary, and so its absorption lines show the characteristic to-and-fro displacement due to Doppler effects. In 1904 it was found that one line, due to calcium, did not share in this movement, but remained obstinately in the same position. Clearly, then, it could not be a line due to the binary itself, and must be produced by material lying between the star and ourselves. Since then many extra proofs of the presence of interstellar matter have been obtained; for instance, we know of B-type stars which appear reddish in hue, and since no B-star can be genuinely red we know that the colour is due to the fact that the light is coming to us through a haze.

The obscuration is most marked near the main plane of the Galaxy, which again is what would be expected. Actually we can never see the true galactic nucleus, because there is too much material in the way. Only in recent years have we found a means of penetrating this material, and no optical telescopes will ever be able to do so.

Another relatively modern discovery is that the whole Galaxy is rotating. There is a great difference between the galactic rotation and the movements of the Solar System; the Earth and other planets are moving round one controlling body, the Sun, while there is certainly no single controlling body in the Galaxy. Yet the rotation round the centre of gravity of the system is real, and the Sun is taking part in it, carrying the Earth and other members of its family along too. Moving at about 150 miles per second, it takes the Sun approximately 225 million years to complete one journev, and this period has been aptly termed the 'cosmic year'.

Here again we are faced with a time-scale which is too great for us to appreciate properly. One cosmic year ago, the Earth was in the period known to geologists as the Carboniferous; the coal forests dominated much of the land, but there were no true trees, and the so-called forests were tall plants of the horsetail variety, among which flitted giant dragonflies. Men and other mammals lay far in the future, and the most advanced life-forms on Earth were amphibians; even the terrible dinosaurs had not yet appeared. Two cosmic years ago, and we are back in the Cambrian period, when the continents were completely barren and life was represented only by small, low-type sea creatures. If we go back three cosmic years we reach the Pre-Cambrian, before life began here. The whole story of living things on our world, then, is contained in the last three cosmic years. What will happen to us during the next cosmic year remains to be seen, though probably it depends to a great extent upon our own actions in the immediate future!

If we could go far out into space and look at the Galaxy from one side, we would see a flattened system with a noticeable central bulge. If we could look from right angles, however, it would become clear that the Galaxy is spiral, not unlike a tremendous Catherine-wheel. A spiral shape was suspected many years ago, but an entirely new branch of astronomical research was needed to prove it.

We can see other galaxies millions of light-years away, and many of these are spiral, so that there were grounds for supposing our own system to be of the same form. But while suspicion is one thing, proof is quite another, and so long as astronomers had to depend solely upon optical methods they were decidedly handicapped. There is another everyday analogy to hand. Not long ago I flew over Alderney at a height of several thousands of feet, and the shape of the island was unmistakable, so that I could easily have drawn a reasonably accurate sketch-map of it. Now consider the position of a man who lives on Alderney but is not allowed to move outside his house and garden; how is he to find out the island's shape merely by inspecting the parts of it which he can see? This was the sort of problem which faced astronomers until very recently. The solution was given by radio methods, which have become so important in modern science that they certainly merit a special chapter in any book.

15

Radio Waves from Space

Radio astronomy has been very much in the news during the past few years, partly because of its importance in studying the artificial earth satellites—Sputniks, Vanguards and the rest—and partly, so far as Britain is concerned, because the largest dish-type radio telescope in the world has been set up at Jodrell Bank, in Cheshire. It is therefore rather surprising to find that many people have odd ideas about it. Some enthusiastic non-scientists even believe that all one has to do is to build a large aerial, turn it to the sky, and then listen in to actual radio noise coming from Mars or a distant star.

This is nearly as absurd as the idea of man-made broadcasts reaching us from outer space. Sound-waves are carried by air; since there is virtually no air above a height of a few hundreds of miles from the Earth, neither can there be any sound. The noise which so many people have heard on various B.B.C. science programmes is produced in the receiver of the radio telescope, and has not travelled to us across space in such a form. It is in fact one method—though by no means the only one—of recording this sort of radiation, and the term 'radio noise' is somewhat misleading.

The story of radio astronomy really began in 1930, when Karl Jansky, a young radio engineer working for the Bell Telephone Laboratories in the United States, built a large and unusual kind of aerial to help him study the static which often interfered with wireless communication. The aerial could be rotated, and was a somewhat improvised contraption nicknamed the 'Merry-go-round'; its four wheels were taken from a dismantled Ford car, and the best description of it is to say that it looked rather like the skeleton of an aeroplane wing. Yet in scientific history its importance is comparable with that of Galileo's first optical telescope.

Jansky began systematic work in 1931, and carried out the programme he had been set. He identified normal static, such as that produced by local thunderstorms, but another noise-source was much more puzzling. In his own words, it was 'very weak and steady, causing a hiss in the 'phones that can hardly be distinguished from the hiss caused by set noise', and it seemed to come from a special part of the sky, a definite point source which moved daily from east to west just as the Sun and stars do. By 1932 Jansky had satisfied himself that the mysterious source lay in the constellation Sagittarius, and was presumably to be identified with the star clouds in the Milky Way there. It is these clouds, remember, which indicate the direction of the galactic nucleus. Before discussing the nature of this new sort of radiation, however, we must say something about wavelengths.

Light may be considered as a wave motion, but it is hopeless to try to measure the distances between successive crests in ordinary

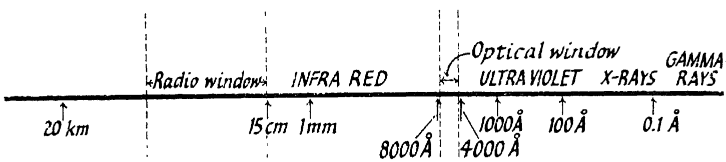

FIG. 37. The Electromagnetic Spectrum. This is a rough diagram to show the two 'windows' to which the Earth's atmosphere is more or less transparent—the optical window, and the radio window. If we wish to observe outside these two ranges, we must send instruments above the atmosphere.

units such as inches. The wavelength of light varies with the colour, but even with light of long wavelength (red light) we have to deal with extremely tiny quantities. The standard unit is the Ångström,* named after a last-century Swedish physicist; one Ångström unit is equal to a hundred-millionth of a centimetre, and visible light extends from about 4000 Å (violet) up to 7600 Å (red). If the wavelength of the radiation is less than 4000 or more than 7600 Å it cannot be seen visually, though it can be detected in other ways.

Most people are familiar with the infra-red lamps used in hospitals. Here the radiation is above the 7600 Å mark, but it is still fundamentally the same as 'light', even though it does not

* It was inconvenient of him to begin his name with the distinctive Swedish Å; in many books this is transformed into a normal letter A—which I regard only as a cowardly evasion, though certainly much easier to type!

affect our eyes. The radiation which Jansky was measuring from the sky had longer wavelength still, and we call such emissions 'radio waves'. The term does not mean that the radiation is artificial!

The whole range of possible wavelengths is known as the 'electromagnetic spectrum', and is much more extensive than might be thought. Our eyes are sensitive to so small a fraction of it that we are badly handicapped, and astronomers are rather in the position of a pianist who is trying to play an instrument whose notes are silent apart from those of the middle octave. (From my own experiences of playing Royal Air Force pianos during the war I know only too well that it is difficult to produce a tune under such conditions, and ideally one needs to be able to use every note from the lowest to the highest.) So long as only part of the electromagnetic spectrum could be studied, knowledge was bound to remain sketchy. Actually the astronomer was in an even worse position than our pianist; a single octave includes about 1/7 the number of notes on a normal keyboard, but the range of visible light is much less than 1/7 of that of the whole electromagnetic spectrum.

A further hazard is that the Earth's atmosphere is transparent only to a narrow range of wavelengths, and blocks out the rest as effectively as visible light is blocked by a brick wall. Our eyes and cameras can record only the radiation which lies within the so-called 'optical window' shown in the diagram, since most of the ultra-violet is absorbed by the upper atmosphere, and some of the infra-red by the lower atmosphere. Fortunately there is also a 'radio window' to which the atmosphere is again transparent, and this is where radio telescopes come in, though at longer wavelengths still the atmospheric blocking returns. Nowadays we can counteract these troubles to some extent by sending instrument-carrying rockets and satellites above the top of the atmosphere, but in the early days of Jansky's research rockets were very feeble and unreliable things, while the very idea of launching an earth satellite or sending a vehicle to the Moon was enough to make the conventional scientist laugh scornfully.

Oddly enough, Jansky's tremendous discovery caused almost no comment at the time. Relatively few people heard about it, and most of those who did so took no notice; moreover Jansky himself was busy with other matters, and never followed up his research into radio waves from the Milky Way. It is true that Grote Reber, an American amateur, built a 31½-foot 'dish' in his back garden in Illinois, and in 1938 confirmed the Milky Way radiation, but very little else was done before the outbreak of war.

The war put a very different complexion on matters, and led to the development of radar, which involves the transmission of a pulse of energy and the subsequent observation of the echo as the energy is 'bounced back' off a solid body or some other object which acts in similar fashion—rather as a tennis-ball will rebound from a wall. Radar defences became vitally important, and so did radio studies in general. By 1945 the situation had changed entirely, and as soon as fighting ceased the scientists were able to return to profitable research. Radio waves from the Milky Way were fully established, but it also became clear that there were other celestial sources not connected with the Milky Way at all. Interest was thoroughly aroused, and radio telescope building was begun in many countries.

The name 'radio telescope' is inclined to mislead the non-scientist, since one cannot look through it in the same way as with an ordinary telescope. Indeed, there is no outward resemblance whatsoever. A dish-type radio telescope of the kind used at Jodrell Bank is more in the nature of a vast aerial, in this case 250 feet in diameter, but it focuses long-wave radiation just as an optical telescope focuses visible light; once this has been done, the radiation itself can be studied. A. C. B. Lovell, Professor of Radio Astronomy at the University of Manchester and the man who has probably done more than anyone else to bring the new science to the fore, has commented that a radio telescope 'is, in effect, a very large version of the common television aerial'. On the other hand not all such instruments are of the wire dish type, and many are superficially quite different, since each is designed for some special investigation.

The Sun might well be expected to be a source of long-wavelength radiation, and it is indeed a powerful source. Most of the emission comes not from the photosphere, but from the corona, though outbreaks such as solar flares produce sudden and violent bursts of radio noise which make themselves very noticeable. The planet Jupiter also produces radio noise, but here the cause may lie in electrical storms in the planet's atmosphere. Radio noise has also been reported from Venus, though with less certainty, and suspected with regard to Saturn. However, most radio sources lie far beyond the Solar System, and are either far away in the Galaxy or else outside it altogether.

The term 'radio stars' used to be favoured, but is unsuitable, since no individual star apart from the Sun is known to be a radio source. The reason is easy to find. The Sun's emission seems powerful only because we are so close to it; remove the Sun to a distance of several light-years, and the radio waves would be too weak for us to detect. Undoubtedly the stars do emit radio waves, but the main sources lie in parts of the sky where there are no conspicuous visual objects, and for some years astronomers were decidedly puzzled. For instance, why should a certain area in Cassiopeia send out powerful waves while a brilliant naked-eye star such as Sirius yielded no result at all?

Gradually, at least some of the answers were found. For the present we will deal only with sources inside the Galaxy, since the others are best left until the next chapter, but even so we have plenty of material.

One of the earliest separate radio sources to be discovered lay in the constellation Taurus, not far from Zeta. In 1949 the position of this source was measured accurately, and proved to be the same as that of the Crab Nebula. Coincidence could be ruled out, and so for the first time a source beyond our Solar System had been identified with an object shown by visual telescopes.

We know a good deal about the Crab Nebula. It is of course the wreck of the 1054 supernova, one of the greatest outbursts to have taken place in the Galaxy since our records began. Since the explosion the outer shell of gas sent out from the old supernova has been expanding rapidly, and now has a diameter of 7 light-years, which is almost equal to the distance of Sirius from the Earth. The gas is in a disturbed condition, and it is this disturbed gas which is responsible for the radio waves picked up in our recording instruments.

The sites of the two other galactic supernovæ, Tycho's star of

1572 and Kepler's of 1604, are marked by radio sources, but in neither case does the strength rival that of the Crab, and no comparable 'nebulæ' are to be seen, though a faint patch marks the position of Kepler's star.

Equally interesting is the intensely powerful source known as Cassiopeia A. It was discovered at an early stage, but was puzzling because at first there seemed to be no visual object anywhere near. Then the British astronomer Smith, at Cambridge, made accurate measures of the radio source and sent his results to Palomar Observatory, with a request for the whole area to be examined with the 200-inch reflector—which was the only telescope in the world capable of such a task. Success came almost at once, and photographs revealed filaments of luminous gas which seemed to form parts of a complete circle. There can be little doubt that these filaments mark the remains of a supernova which exploded long ago, probably before men appeared on Earth.

In addition to old supernovæ, radio sources have been identified with large, almost circular gas clouds of which the Veil Nebula in Cygnus is a good example, and with glowing clouds of diffuse hydrogen (or, to be more exact, ionized hydrogen) surrounding certain very hot stars of early spectral type. There is also the source in the direction of the Sagittarius star-clouds. The general view is that this does indeed mark the region of the galactic centre; some authorities think that the actual source is much closer to us, and that we are being misled by a chance lining-up, but such a coincidence would be really remarkable.

On occasions there are opportunities for amateur radio astronomers to do very useful work. Such a chance came in June 1959, when the Crab Nebula was occulted by the Sun's corona, so that radio waves from the Nebula had to pass through the corona in order to reach us. By studying what happened, it was possible to learn more about the solar corona itself, and among those who tackled the problem were workers of the Radar and Electronics Section of the British Astronomical Association, directed by J. Heywood. Special instruments were built, and set up at Clacton, Radley, and Crawley Technical College specifically to observe the occultation, with good results. Vast and complex instruments of the Jodrell Bank type take years to build at a cost of hundreds of thousands of pounds, and it is worth remembering that a good deal can be done even with modest equipment.

Now let us return to the question of the spiral shape of the Galaxy.

So many of the outer galaxies are spiral that it had long been thought that our system might be of the same kind. The first vague proofs were given by optical astronomy, when W. Baade, in America, pointed out that in other galaxies—and therefore presumably in our own—there were two distinct types of 'populations'; the first (Population I) in regions where there was considerable dust and gas, and where the brightest stars were very luminous early-type objects of spectra O and B; the second (Population II) in regions almost clean of dust and gas, and where the leading members were red supergiants. It appeared that globular clusters and the centres of galaxies were mainly Population II, while the spiral arms of galaxies were mainly Population I. By plotting the distribution of the very luminous O and B stars in our own system, inconclusive signs of spiral structure appeared.

All this was very uncertain, but a solution was to hand. We know that of all interstellar gas, hydrogen is much the most plentiful; it tends to collect into huge clouds some 30 light-years across, and is very cold, with a temperature of about −150°C. Naturally it is very rarefied, and there are less than 10 atoms per cubic centimetre, which is an extremely low density judged by any standards. Optical telescopes will not show it at all.

In 1944 a Dutch scientist, van de Hulst, worked out that even at this low temperature the interstellar hydrogen should be emitting radio energy on a wavelength of 21·1 centimetres. He knew that it would be weak and hard to detect, but he was convinced that sooner or later it would be found. Unfortunately, conditions in Holland at that time made all proper scientific work impossible; the Germans were still in occupation, and van de Hulst had to bide his time. It was not until six years after the war had ended that two Harvard researchers, Ewen and Purcell, actually tracked down the feeble 'noise' on 21·1 centimetres and proved that it did in fact come from hydrogen in space.

Among all the splendid achievements in twentieth-century astronomy, van de Hulst's must rank in the top flight. It is even more important than might be thought, because the 21-centimetre radiation is concentrated into a narrow band of wavelengths instead of being spread out; it forms what is equivalent to a spectrum line, even though it cannot be seen visually. Spectrum lines can yield Doppler shifts, and the 21-centimetre line is no exception, so that astronomers have been able to investigate not only the distribution of the hydrogen but also its movement toward or away from the Earth. Neither is the radio emission blocked by obscuring material, and we can therefore use it to study regions near the galactic centre, which are quite out of reach even with the largest optical telescopes we are ever likely to build.

By studying other galaxies, we can tell that with a spiral the main concentration of obscuring matter—and hence also the main concentration of hydrogen—is contained in a relatively narrow 'sandwich' in the main plane (shown in the diagram on page 162) and in the spiral arms. By using the 21-centimetre line to plot the hydrogen, then, we can also plot the Galaxy's spiral arms, and this is what has been done. The results are by no means complete, and there is some disagreement between different researchers, but it looks as though five definite arms have been traced. Two of these are closer to the galactic centre than we are, and two farther away, while the Sun itself lies near the inner edge of the fifth or Orion arm. To an outside observer we may be confident that the Galaxy would show up as a rather loosely-wound spiral, very much like many other systems which we can see far away in space.

The Galaxy does not rotate in the manner of a solid body, except perhaps in its innermost parts. In general, the outer regions move more slowly than those closer to the centre, just as in the case of the Solar System, where the outer planets are the slowest travellers. The interstellar hydrogen too takes part in this rotation, and has given us much of our information about it. Very recently J. H. Oort, of Leiden in Holland—a colleague of van de Hulst's, and famous for his work in radio astronomy—has reported the detection of a comparatively small disk of hydrogen gas at the centre of the Galaxy, notable for its quick rotation; but not much is known about this feature as yet.

Radio astronomy has made vast strides since its humble beginnings in 1930 with Karl Jansky's improvised merry-go-round. It will never supersede optical astronomy, since the two branches are complementary and are in no sense rivals, but it can certainly provide us with knowledge which we could never gain in any other way. The 250-foot 'dish' at Jodrell Bank and the various other radio telescopes set up in different parts of the world are as important in their own way as the 200-inch reflector on Palomar or the 236-inch reflector now being built in Russia. Yet come what may, it is hard to believe that they will often give science a greater impetus than during the decade following the end of the war, when radio astronomers proved conclusively that the Galaxy in which we live is a whirling spiral.

16

The Outer Galaxies

Until only a few hundreds of years ago it was generally believed that the Earth must lie in the centre of the universe, and must consequently be the most important body of all. Human vanity suffered a severe blow when men such as Copernicus, Galileo, and Kepler proved that nothing could be further from the truth, but it was still thought that the Sun must be of real significance. When it was shown that the Sun is only one of thousands of millions of similar suns in the Galaxy, there was still one comforting thought left: the Galaxy, at least, was the major feature of the universe.

Sir William Herschel was not so sure. As we have seen, he divided nebulæ into two main classes: those which could be resolved into stars, of which the Great Nebula in Andromeda was the best example, and those such as the Sword of Orion, which could not. With regard to the so-called resolvable nebulæ, he once wrote that they might be 'no less than whole sidereal systems' which might well 'outvie our Milky Way in grandeur'. He could not be certain, since in his day the distances of even the nearest stars remained unknown, but at least he had put forward an exciting idea.

Toward the middle of the nineteenth century, a giant telescope was built at Parsonstown, in Ireland, by the Earl of Rosse. It had a 72-inch mirror, and was thus easily the most powerful telescope constructed up to then; it was a curious-looking instrument, and must have been remarkably awkward to use, but it was certainly effective. In 1845 Rosse turned it toward one of the 'resolvable nebulæ', M.51, which lies in Canes Venatici not far from the Plough. To his amazement he was confronted with the picture of a whirlpool of light—a true spiral, unlike anything which had been seen before. This was the first indication that some of the nebular objects might be spiral, but in the following years others were found, and by 1850 the list had grown to fourteen. Nowadays so many are known that to catalogue them would need a very thick book.

Particularly interesting is the Andromeda nebula, which is the only one of Herschel's 'resolvables' visible to the naked eye as seen from northern latitudes. Here too we have a spiral, but unfortunately we are looking at the system from an angle, so that the spiral effect is partly lost. If we had a bird's-eye view of it, as with M.51, it would be much more spectacular.

Though more and more spirals were found, it also became clear that some of the 'resolvables' were entirely different. There were circular nebulæ, easily confused with globular clusters; others were

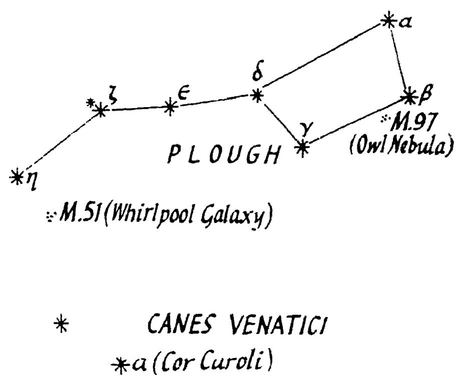

FIG. 38. Positions of the Whirlpool Galaxy, M.51, and a famous planetary, the Owl Nebula (M.97). Unfortunately, large telescopes are needed to show them well.

elliptical, while a few were entirely irregular in outline. Moreover, no astronomer could be certain whether we were looking at external systems, or at features which lay well inside our own Galaxy. On the whole, opinion had swung away from Herschel's guess, and in a famous history of astronomy written in 1902 by Agnes M. Clerke we find the theory referred to as 'a half-forgotten speculation . . . it becomes impossible to resist the conclusion that both nebular and stellar systems are part of a single scheme'.

The resolvable nebulæ are so remote that all parallax methods of distance-gauging break down, and for a time it looked as though the problem would be impossible to solve. Then, rather unexpectedly, the first real clue was given by certain stars in the two

Nubeculæ or Magellanic Clouds, so named because attention to them was first drawn by the explorer Magellan during his voyages in the southern hemisphere.

There are two Clouds, both prominent naked-eye objects. The larger is so conspicuous that even bright moonlight will not overpower it, and a telescope reveals all sorts of objects, including variable stars and gaseous nebulæ. The Small Cloud, Nubecula Minor, is of the same type, and it too is bright, though moonlight will drown it. Northern observers never cease to regret that neither Cloud is visible from our latitudes.

Around the beginning of the present century, thousands of photographs of the Clouds were taken from Arequipa in Peru, where a large telescope had been set up by astronomers of Harvard University. These plates were carefully studied by Henrietta Leavitt, one of the several women who have made outstanding contributions to astronomy, and some interesting facts emerged. Over 1750 variables were detected, many of which were Cepheids. Miss Leavitt plotted the light-curves of these Cepheids, and found that the brightest had the longest periods; there was a definite law about it, and there seemed to be no exceptions.

The crux of the whole matter was that for most practical purposes the variables inside the Clouds could be regarded as being at the same distance from us. (If you ask a Glaswegian how far his city is from London, he will not bother to ask whether you mean Victoria or Charing Cross, since the distance between these two stations is negligible compared with the much greater distance between Glasgow and London as a whole; for comparison we may compare London with the Earth, and the two stations to a couple of Cepheids inside the Cloud.) So by arranging the Cloud Cepheids in order of apparent brightness, Miss Leavitt also arranged them in order of real brightness; the longer-period stars really were more luminous than those which fluctuated more quickly. This, of course, was the famous Cepheid period-luminosity law which has become so vitally important in astronomy. It was not long after this that Harlow Shapley studied the Cepheids in the globular clusters, and gave us the first reliable map of the Galaxy.

Actually, the stars used by Shapley were not classical Cepheids, but the 'cluster-Cepheids' now known as RR Lyræ variables. The difference appeared to be unimportant at the time. It proved to be of the greatest significance later on—but that lay well in the future.

What could be done for the globular clusters could presumably be done also for the resolvable nebulæ, and this would settle the vexed question as to whether they lay beyond our Galaxy. The only trouble was that for some time no Cepheids could be detected in the Andromeda Nebula, which was the brightest member of the class—excluding the Magellanic Clouds—and therefore the most promising. Finally, in 1923, E. P. Hubble, at Mount Wilson, made a fresh search with the 100-inch reflector, and met with success. He identified a dozen variables, worked out their distances, and announced that the Andromeda Nebula must be roughly 750,000 light-years away.

There could be no doubting that this result was of the right order, and it showed that Herschel's guess had been correct. Far from being members of our system, the 'resolvables' lay far beyond it, and were galaxies in their own right. The term 'resolvable nebula' dropped out of favour, to be replaced by the more accurate term 'galaxy'.

Further studies indicated that Hubble's original estimate was too low, and that 900,000 light-years would be better. Even so, it appeared that the Andromeda Galaxy was much smaller than ours, and most astronomers still believed the Milky Way to be a sort of super-galaxy well above the average in every respect.

Then, some ten years ago, W. Baade began to study the Andromeda Galaxy with the aid of the new 200-inch reflector at Palomar. His aim was to find some RR Lyræ stars, since up to then no such variables had been found anywhere except in our own system. Greatly to his surprise, he failed completely. There did not seem to be any RR Lyræ stars at all, and logically there should have been; after all, they are considerably more luminous than the Sun, and at a distance of 900,000 light-years the Palomar telescope should have shown them easily.

There were only two possible solutions. Either the Andromeda Galaxy was completely devoid of RR Lyræ variables, or else the system itself was farther away than had been thought, so that the RR Lyræ stars would be too faint to show up. The first alternative could be ruled out, and in September 1952 Baade provided his fellow astronomers with a major shock. He showed that our whole distance-scale of the universe was wrong.

Remember that in his mapping of our Galaxy Shapley had used RR Lyræ stars, not classical Cepheids. His results were valid, since his estimates of the luminosities of RR Lyræ stars were correct. What neither he nor anyone else had realized was that there are two types of short-period variables: those of Population I (including the classical Cepheids) and those of Population II (including the RR Lyræ stars), and there is a very marked difference between them. A Population I Cepheid is much more luminous than a Population II variable of the same period.

The Cepheids used by Hubble to measure the distance of the Andromeda Galaxy were of type I—but the distances had been worked out on the assumption that they were of type II. Therefore, since the Cepheids were much more luminous than had been thought, they had to be much farther away, and this at once accounted for the apparent lack of RR Lyræ stars; at such a distance they were too faint to be seen individually.

The net result was that the distances of all objects beyond our Galaxy, including those of the Nubeculæ, had to be doubled. Instead of being 900,000 light-years away, the Andromeda Galaxy was more like 2 million light-years from us.

Actually, the Magellanic Clouds provided an extra proof. They contain globular clusters, but up to then there had been a curious anomaly; though similar in form to the globulars in our Galaxy, the objects in the Clouds had been thought to be only a quarter as brilliant. Assuming the Cloud globulars to be as luminous as our own, the Clouds themselves would have to lie at a distance of about 150,000 light-years instead of the formerly-accepted figure of 75,000 light-years. This fitted in excellently with the new Cepheid scale, and in fact every piece of the jig-saw puzzle fell into place.

At its revised distance, the Andromeda Galaxy was found to be considerably larger than ours. No longer could we picture ourselves as living in an exceptional system; Man's last illusion was shattered.

M.31 is not the only galaxy visible with small or moderate telescopes, and in fact Messier's original catalogue contains 38 objects which are now known to be galaxies. The Nubeculæ are not included, since they can never be seen from the latitudes in which Messier lived.

The Nubeculæ remain the nearest known of the external systems, and it seems certain that none are closer. In some ways they may be regarded as junior companions of our Galaxy. The Andromeda Galaxy has two companions of its own, one of which was listed by Messier, but unlike the Nubeculæ these companions are elliptical, and seem to be predominately Population II, so that the

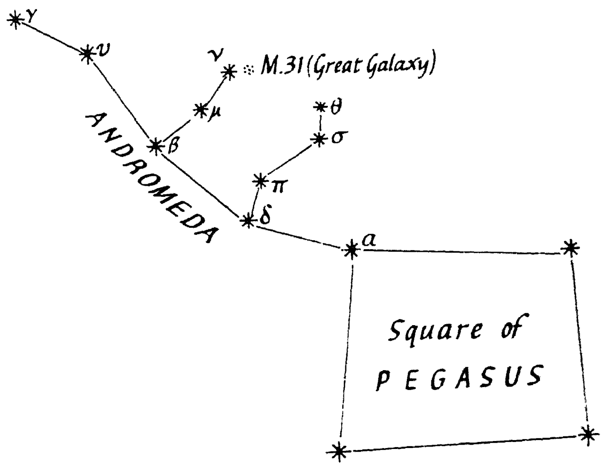

FIG. 39. Position of M.31, the Great Galaxy in Andromeda. The Galaxy is clearly visible to the naked eye on a clear night if you know where to look for it. The 4th-magnitude star ν Andromedæ is the best guide.

brightest members are reddish. Hot main-sequence stars of high luminosity are lacking, though there are plenty of them in M.31 itself.

Farther away than the Nubeculæ, but slightly closer than the Andromeda Galaxy, is another spiral—M.33, in the little constellation of Triangulum. Moderate telescopes will show it, but it is relatively faint, and the spiral form is not visible except with large instruments. The fact that it is both nearer and dimmer than the Andromeda Galaxy shows that it is genuinely fainter, and this is what we find, since modern Cepheid measures place it at a distance of about 1½ million light-years.

The Andromeda and Triangulum spirals, the Nubeculæ, and our own system are members of what is termed the Local Group of galaxies. Since these are our neighbours in space on the astronomical scale, their distances can be judged with more accuracy than is possible for remoter systems, and we can also photograph their structure. If we take the Local Group as being fairly typical, we can presumably arrive at a fairly reliable estimate of the percentages of different types of galaxies. The result of such analysis is unexpected, because spirals seem to be in a minority. Altogether the Local Group contains three spirals (our Galaxy, M.31 and M.33) and two irregulars (not counting the Nubeculæ, which some authorities believe to be very ill-defined spirals). The remaining 10 are elliptical, and much less brilliant. Of these the dwarf galaxies in Ursa Minor, Draco, and Sculptor are not much more remote than the Nubeculæ, but were not discovered until recently, partly because of the lack of luminous early-type stars and partly because their forms are so vague. Such dwarf galaxies are made up of Population II objects, including RR Lyræ variables.

So far, so good. The RR Lyræ stars and the classical Cepheids between them have shown us the scale of the universe, and though the measured distances of galaxies in the Local Group are far from precise they cannot be wildly wrong. For remoter objects the problems become greater, since beyond about 3 million light-years even the Cepheids fade into the general starry blur, and we lose our priceless 'standard candles'. We must look for something to take their place.

Cepheids are very luminous, but cannot rival the really powerful supergiants, and it has been found that the most luminous stars in any spiral galaxy are roughly equal; for instance, the leading supergiants in our Galaxy are about as luminous as their counterparts in M.31. These supergiants can be seen individually well beyond the Cepheid range, and by measuring their apparent magnitudes we can gain some idea of how far off they are. The results are less accurate than for Cepheids, but are a good general guide, and the method can take us out to 20 to 25 million light-years.

This is where good fortune comes to our help. At about 15 million light-years we find a whole group of galaxies, the so-called Virgo

Cluster;* it contains over 1000 members, and for most practical purposes all these galaxies can be regarded as at the same distance from us. They appear fairly close together in the sky, but this is liable to give a misleading impression; actually they are widely separated, though admittedly closer to each other than the members of our Local Group.

The supergiant method can help us to estimate the distances of the Virgo galaxies, and we can then work out how big the various galaxies are. From this, it is possible to deduce the average size of galaxies of different kinds. Beyond about 25 million light-years we lose even the supergiants, and no individual stars can be made out, but by measuring the apparent size of the galaxy concerned we can work out its distance—provided we know its real dimensions, which may be estimated from our studies of the Virgo Cluster.

Again we have a reduction in accuracy, because even if two galaxies are similar in form they are not necessarily equal in size, but the method is far better than nothing at all, and it can take our 'space soundings' out to over 2000 million light-years. Sometimes, of course, extra checks are possible. Supernovæ occur in galaxies other than our own, the most famous example being the 1885 star in M.31; if we assume an average maximum luminosity for supernovæ, we can obtain their distance.

Generally speaking, the average distance between galaxies seems to be something like 3 million light-years, but we must remember that except in our own part of the universe we can see only the brighter systems. If the Nubeculæ, or the companions of M.31, lay at—say—500 million light-years they would not be detectable, though a major galaxy would still show up well. The tendency toward clustering is marked, so that many astronomers believe the true picture to be one of vast arrays of groups, genuinely isolated galaxies being rare exceptions.

The most distant galaxies yet studied, such as those of the Hydra Cluster, are at least 2000 million light-years off. Only the Palomar 200-inch reflector is capable of photographing them, and of course no structure can be seen; the galaxies appear only as fuzzy patches, and at a casual glance might easily be mistaken for

* Remember that a cluster of galaxies is very different from what we usually term a star-cluster.

ordinary stars. The photographs of the Hydra Cluster obtained at Palomar may not look spectacular, but are probably among the most exciting ever taken, as will be seen when we remember that each diffuse speck is really a collection of thousands of millions of stars together with globular clusters, nebulæ, and quite possibly Solar Systems as well.

This is as far as modern optical methods can take us. Larger telescopes will extend the range still farther, and it is much to be hoped that the reported Russian 236-inch reflector will be completed before long, but the last word so far has been said by radio astronomers. First, however, let us say something more about the galaxies which are close enough for their structure to be examined.

Spirals are of various kinds, from loosely-wound forms to 'tight' Catherine-wheels. Years ago Hubble divided them into

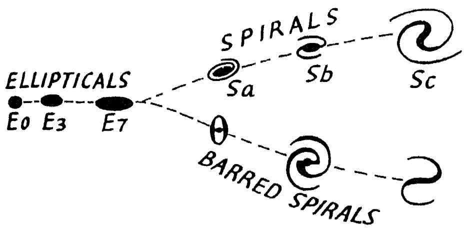

FIG. 40. Classification of galaxies. Whether this represents some kind of evolutionary sequence is still uncertain.

types—Sa, Sb, and Sc—and this, together with the rest of his classification system, has been retained. In Sa, the central nucleus is large, with the arms small and tightly coiled as in the remarkable galaxy known popularly as the Sombrero Hat. Sb objects have arms which are more prominent, and the Andromeda Galaxy belongs to this class; so too does M.81 Ursæ Majoris, a giant system 7 million light-years away, as well as the famous Whirlpool in Canes Venatici. When we come to Sc, we find a much looser arrangement, which may sometimes be so untidy that it is not easy to trace the spiral form at all. M.33 Trianguli is an example of a less extreme Sc galaxy, while our Galaxy is to be believed to be of type Sb, though it is probably more loosely wound than M.31.

We have seen that the nucleus of a galaxy consists mainly of

Population II objects, with a relative absence of interstellar gas and dust. Sa galaxies, therefore, are mainly Population II; Sb contain both Population II (in the nucleus) and I (in the arms), while Sc are mainly Population I.

In addition there are the extraordinary barred spirals (SBa, SBb, and SBc) in which the arms seem to extend not from a true nucleus, but from the ends of a straight bar lying in the plane of the system and passing through its centre. These objects are less common than normal spirals, since the proportion is about one to three, but all the same there are plenty of them, and it has been suggested recently that the Magellanic Clouds may be basically of this class.

Genuinely irregular galaxies are rare, though they do exist. Much commoner are the ellipticals, which are divided into seven sub-grades ranging from flattened forms (E7) down to perfect spheres (E0). From 15 to 20 per cent. of bright galaxies are of such a type, but the percentage is almost certainly higher for faint galaxies; remember that in our Local Group there are 10 ellipticals and only 7 others, at least so far as we know at the moment. The ellipticals consist mainly of Population II.

It is rather tempting to suppose that a typical galaxy begins as an elliptical, or rather spherical, system (E0) and that its rotation flattens it out, so that it moves along to E7 and ultimately becomes a spiral. Unfortunately this does not fit the facts, because we have to take the different Populations into account.

Population I, as we have seen, contains very hot stars which are squandering their energy and material so rapidly that they cannot last for long on the cosmic time-scale. Consider, for instance, the Nubecula Major. Here we have many early-type supergiants, including the famous S Doradûs, which is something like a million times as luminous as the Sun and must be short-lived; we also have vast gaseous nebulæ, and a tremendous amount of interstellar material from which, presumably, fresh stars are being formed all the time. Everything indicates that the whole Cloud is young. More closely-knit spirals contain both young and old features, but in the elliptical systems Population I is negligible, so that we have a much more sedate picture. Most of the interstellar material has been used up, and the hot early-type supergiants have disappeared, to be replaced by later-type leaders which are further advanced in their careers. Here, too, we have more frequent novæ and supernovæ; this fits well into the scheme, since it is very probable that no star can suffer a nova-like outburst until it has exhausted much of its hydrogen fuel and is coming to the end of its tether.

In fact, Population I is young, while Population II is old. There is a steady increase in the percentage of Population II from the loose spirals (Sc and SBc) to the ellipticals, and so this may be the direction along which a galaxy develops, though as yet there is no general agreement among astronomers. On one theory, a galaxy begins as an irregular, turns into a spiral because of its rotation, and becomes elliptical as its rotation slows down, ending up as a spherical system of class E0; but it has also been suggested that the key to the whole problem is the original rate of spin, so that quick-spinners will become spiral and slow-spinners elliptical. In a few cases we can learn something about the present rate of rotation, particularly with M.31, but so far our information is rather scanty.

We have indeed come a long way during the last 60 years. We have found that Herschel's resolvable nebulæ are true galaxies, some of them greater than our own; we have found the distances of many, and we have learned that our glorious system, with its hundred thousand million stars, is no more important than a cupful of water in the Atlantic Ocean. It is time for us to turn to what may be the most vital problem of all: How did the universe begin, and how will it end—if indeed it will end at all?

17

The Universe

Men have always wondered how the universe began. This is a natural feeling, and we need not be ashamed that so far we have failed to find out. We are faced with a stupendous problem, and our only hope is to gain what information we can, gathering it and doing our best to sort it out so that it makes some kind of sense.

We can be reasonably confident that the Earth was formed by some process involving the Sun, possibly from material picked up when the Sun passed through a 'cloud in space' thousands of millions of years ago. We may be equally confident that the Sun and other stars were formed out of interstellar material. The crux of the whole matter is: How did this galaxy-making material get there in the first place?

It is not easy to give a good analogy, but let us put ourselves in the position of a solitary artist who is given an elaborate coloured painting and is asked to explain its origin. He will presumably begin by studying the various colours used, and if he can submit them to chemical analysis he will be able to find out what materials make them up. So far, so good. But we are supposing that the artist is simply confronted with the finished picture, and has no idea of how paints are manufactured. Now he is in a quandary, and there are two courses open to him. He can evade the issue by saying vaguely that the original paints were 'created', after which he can trace the whole story up to the moment when the picture is completed; alternatively, he can try to go into the process of providing the raw materials.

Only a few centuries ago, Archbishop Ussher of Armagh adopted the first method, and stated that all the matter in the universe was divinely created at a special moment in the year 4004 B.C. This did not fit any of the facts, because geology showed that the Earth is far older than a mere 6000 years. If however we are prepared to revise Ussher's time-scale, and replace his 4004 B.C. by—say 40,000 million B.C., we can draw up a history of the universe which begins with primæval material, and passes through galaxies and stars until reaching planetary systems. Yet we have simply dodged the main point, because we have made no attempt to explain the mystery of the creation itself.

Incidentally, it is often said that there are two opposing view-points, the religious and the scientific, so that astronomers who try to delve into fundamentals and discover something about the formation of the universe are rejecting the whole idea of divine creation. Nothing could be further from the truth. Even if we could explain the creation on a strictly scientific basis, there is no reason why it should not still be regarded as divine. This is at least one case in which religion and science do not conflict with each other.

One trouble, evident at once, is that we cannot explain 'time' in ordinary language. If we adopt the Ussher principle, and maintain that the universe began at one particular moment, we are bound to wonder what was happening at a still earlier period. We are equally unable to picture a time-span which has no beginning, and extends backward for ever.

To put our ideas in order, it may be helpful to give a brief summary of conditions in the present-day universe, and to see what 'paints' we can give to our imaginary artist.

First there are the galaxies, which tend to collect into clusters; our Local Group is one such cluster, and there are many others, such as the Virgo group (over 1000 members, distance 15 million light-years), the Leo group (300 members at over 300 million light-years) and the immensely more distant Hydra group at roughly 2000 million light-years, near the limit of visibility with the Palomar reflector. Clusters of galaxies which are more remote still are too faint to be seen with our present telescopes.

Each galaxy contains thousands of millions of stars, together with vast quantities of interstellar material, but at the moment we are concerned only with the original galaxies. Once we can explain their origin, we can trace the later events if not with certainty, at least with some degree of probability. In particular, then, we must study the way in which the galaxies are behaving, and here we must turn back to the spectroscope.

The spectrum of a galaxy is bound to be confused. It does not emanate from a single body, but is the result of the spectra of all kinds of objects jumbled together, so that only the main lines can be made out. Really detailed analysis is virtually impossible, but at least it should be practicable to obtain Doppler shifts, and these will—as usual—indicate velocities; a red shift means recession, a violet shift means approach.

In 1920 V. M. Slipher, at the observatory founded at Flagstaff by Percival Lowell, examined over 400 galaxies, and made a curious discovery. Violet shifts were almost absent; red shifts were not only the rule, but almost an invariable rule. Nearly all the galaxies

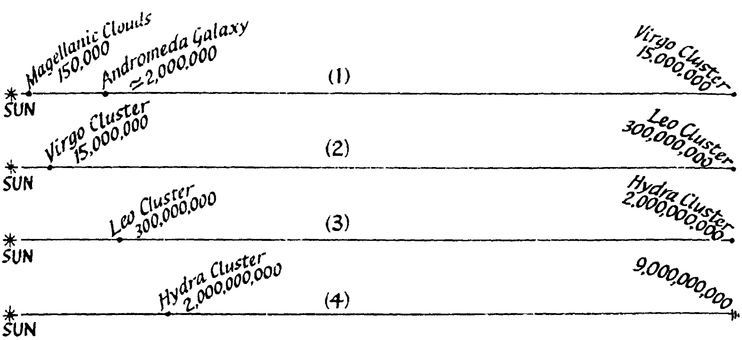

FIG. 41. Distances of galaxies. (All distances are given in light-years.)
(1) The Magellanic Clouds, the Andromeda Galaxy, and the Virgo Cluster.
(2) The Virgo and Leo Clusters.
(3) The Leo and Hydra Clusters. The Hydra Cluster lies at about the limit of range of the Palomar reflector.
(4) The Hydra Cluster and the 'vital distance' of 9000 million light-years.
It is clear that we still have a long way to go!

were running away from us at speeds up to 1000 miles per second. At that time it was still uncertain whether the 'spiral nebulæ' were members of our own system or whether they lay beyond, and Hubble's classic observations of the Cepheids in M.31 still lay in the future, but on all counts the red shifts were very much of a problem.

When Hubble had managed to show that the spirals were true galaxies, he turned his attention to the red shifts. What he found made the situation even stranger. If the Doppler results were to be believed, the galaxies were certainly receding—and the farther away they were, the faster they went. For instance, a galaxy 10 million light-years distant would recede much more rapidly than another at only 5 million light-years, and so on. Together with his colleague Milton Humason, Hubble was able to show that there was a definite link between recession and distance, so that once a galaxy's distance could be determined its velocity away from us could be worked out. At that time the largest telescope in the world was the Mount Wilson 100-inch, and Hubble and Humason could reach out to a cluster of galaxies in Ursa Major, which we now know to be 700 million light-years away and to be receding at 26,000 miles per second.

By 1936 Hubble and Humason had worked out the speeds of more than 100 galaxies. Then, after the war, the Palomar reflector became available, and the work could be carried on. So far the most distant galaxies known lie at about 2000 million light-years, and are speeding away at 37,000 miles every second. If it has taken you ten minutes to read the first part of this chapter, the receding galaxies have drawn away from us by about 22,000,000 miles since you started.

There is no suggestion that our own Galaxy is particularly unpopular from a cosmic point of view. A moment's thought will show that basically every galaxy is receding from every other, so that the whole universe is expanding. This does not imply that the various clusters of galaxies are disintegrating, but at least we can be sure that each group is running away from each other group.

Even in astronomy, where we have to deal with vast speeds and distances, this picture is extremely difficult to accept, and many attempts have been made to explain the red shifts in some other way. It has been suggested, for instance, that light is robbed of some of its energy during its long journey from a distant galaxy to ourselves, so that it shows a red shift which is not a Doppler effect at all. However, no such theory can, apparently, explain more than a part of the shifts observed. All the evidence shows that we are looking at genuine Doppler shifts, and if this be so there is no escape from the picture of an expanding universe.

If we admit the validity of the Hubble-Humason 'law' linking recession with distance, and if we assume that the law has always operated, we can check upon when the expansion began. It can be shown that some 9000 million years ago all the galaxies must have been relatively close together, whether or not they then existed in the true 'galaxy' forms which we know today. This agrees satisfactorily with our estimates of the age of the Solar System (4000 or 5000 million years), but of course it does not necessarily represent the age of the universe itself.

One of the first men to draw up a modern-type theory of the beginning of the universe was a Belgian priest, the Abbé Lemaître. Lemaître's conception was of a very dense 'primæval atom' comprising all the material in the universe. The density of this primæval atom would have to be stupendous, and a hundred million tons per cubic centimetre would be a conservative estimate, so that there would be no proper elements as we know them, and certainly no individual galaxies. Then, between 20,000 million and 60,000 million years ago, the primæval atom exploded, sending its material outward in all directions. Expansion, the direct result of this outburst, went on for thousands of millions of years, until the whole universe had a diameter of perhaps 1000 million light-years. At this stage things began to settle down, and the clusters of galaxies began to form from the primæval material.

We know that gravitation tends to draw material together, and one might imagine that as soon as the force of the explosion had spent itself the matter in the universe would move once more toward a common centre. Lemaître supposed that this did not happen for the excellent reason that there is another force, cosmical repulsion, which acts in the contrary fashion to gravity over very great distances, though over small distances—such as those within our Solar System, or even within our individual Galaxy—it is negligible. If so, the 'settling-down' universe would be in a state of balance, cosmical repulsion just counteracting gravity and preventing either a general expansion or a general contraction. Then, about 9000 million years ago, some other disturbance tipped the scales in favour of cosmical repulsion; expansion began, and has continued ever since, because a larger universe means that cosmical repulsion will grow stronger while the opposing forces grow weaker.

Lemaître was only one of those who pictured the story of the universe in this kind of way. Among others who investigated the idea, mention must be made of Sir Arthur Eddington, who is remembered by scientists for his brilliant theoretical work and by non-scientists for his popular books and lectures. In recent years George Gamow, who lives and works in the United States, has advanced a theory which differs from earlier ones but is based on roughly the same principles.

According to Gamow, there is no need for cosmical repulsion, since the present expansion of the universe is due solely to the force of the original outburst. Gamow has worked out the initial temperatures very precisely; on his view, the temperature five minutes after the expansion began was 1000 million degrees, and dropped to 40 million degrees after one day,* falling steadily until reaching a stable value millions of years later. He believes, too, that all the chemical elements so familiar to us now were formed within half an hour after the universe began. There was no long-drawn-out state of balance, as in the older theory.

This is all very well, but we are still no further toward solving the main issue. By starting with the primæval atom, whether on Lemaître's theory or on Gamow's, we can admittedly trace a more or less convincing story through until we reach the present day. It is fragmentary, and parts of it are highly dubious; we are in the position of a man who is trying to read a letter typed on a machine which has only two vowels and half a dozen consonants. Moreover, we have not explained how the primæval atom itself was created, and we have not done more than touch on the mystery of the time-scale. Was there a still earlier period?

This question of 'the beginning' crops up again and again, simply because it is impossible to visualize. Things might be easier in some ways if we could abolish 'the beginning' entirely, and this is what three astronomers working at Cambridge tried to do some years ago, when Hermann Bondi, Thomas Gold, and F. Hoyle put forward their now-famous theory of continuous creation.

Let us go back to the expansion of the universe. Light travels at

* 'Day' here indicates a period equivalent to twenty-four of our hours, and has no direct association with the rotation of the Earth—since in the early days of the universe, the Earth did not exist.

186,000 miles per second; the most distant galaxies visible from Palomar are travelling away from us at almost 40,000 miles per second, which is an appreciable fraction of the velocity of light. If we could use an even more powerful telescope we could reach farther into space, so that the galaxies we could see might be moving away even more rapidly. Eventually we might expect to reach a point when we would meet with galaxies receding at the full 186,000 miles per second. If such speeds were valid, we could not see these galaxies at all, no matter how strong our equipment; they would have passed over the boundary of the observable universe.

On the so-called 'evolutionary' theories of Lemaître and others, the heavens in the very remote future will present a picture different from that which we know. Since the galaxies are moving away at speeds which increase as their distances from us increase, there must come a time when all of them will have passed beyond the observable universe, in which case the sky will be empty of galaxies. Of course, the time-scale is immensely long; as Eddington once said, we need be in no hurry to study the galaxies before they vanish from our sight!

The Cambridge astronomers reject this scheme of things entirely, and also throw overboard the primæval atom, whether on Lemaître's pattern or Gamow's. They suppose that the universe has always been, and always will be, in much the same state as it is now. They do not abandon the expanding universe; the Doppler measures are regarded as valid, and so the galaxies now visible will finally pass beyond observation—but as they vanish, new galaxies will appear to take their place. It follows that new material is being created out of nothingness all the time, and that the universe is in a steady state. The average density of material in any part of the universe remains constant.

It is not supposed that a new galaxy can appear ready-made in an instant. Matter is created in the form of hydrogen atoms, and the rate of creation is comparatively very slow, though over the whole observable universe it amounts, in tons, to a figure 1 followed by 32 zeros per second. When the hydrogen is created, the cycle begins; with majestic slowness the material collects, and galaxies form. On the steady-state theory, then, a being who lives in the very distant future will see the same number of galaxies as we do today—but they will not be the same galaxies.

Unfortunately there is no direct test to hand. There is not the slightest possibility of our being able to detect the newly-created material, any more than one could be expected to detect the formation of a single grain of dust over an area the size of North America. Neither is it at all likely that we will ever be able to do so, and confirmation, if it comes, must be by a roundabout method.

Nobody has yet suggested *how* the matter is created. As Hoyle has said: at a certain time it does not exist, while at a later time it does. Some people object to the whole idea simply because they cannot visualize how material can appear in such a manner. However, the older theories are subject to the same difficulty, since it is equally impossible to understand how the primæval atom can just have appeared out of nothing.

Let us sum up the two rival theories as concisely as we can.

The evolutionary theory supposes that all the material in the universe was created at one moment, so that there was a definite 'beginning'. Expansion began, and galaxies were produced; these galaxies are now receding from each other, and the expansion will continue indefinitely, so that at last the galaxies will lose all contact with each other. Eventually, too, the whole universe must die. It is rather like a clock which is running down and can never be rewound.

On the steady-state theory, the universe has existed for an indefinite period, and has always been in much the same condition as it is now. Individual galaxies die; but since matter is being created out of nothingness all the time, old galaxies are replaced by new ones. The average quantity of matter in any given volume of space remains constant, and there is no reason to think that the universe will ever die. In this case, as our 'clock' unwinds, it is being steadily wound up.

These two theories are as different as the proverbial chalk and cheese, and to decide between them seems at first sight to be a hopeless task. Even if the steady-state idea is correct, we have no chance of checking on it directly, and we must approach the problem differently. What may prove to be the key is the fact that when we look out into space, we also look back in time—a fact which is not always easy to remember. When we look at the Sun, we see it as it used to be about 8·3 minutes ago, because sunlight takes about 8·3 minutes to reach us. The nearest star, Proxima Centauri, is 4·3 light-years away, so that an observer studying it in—say—1960 will see it as it used to be in 1956. When we look at M.31, the Great Spiral in Andromeda, we see it as it used to be about 2 million years ago. This is very little when we are using the cosmic time-scale, but 2000 million years is another matter altogether, and the Palomar reflector can probe far enough to show us galaxies as old as this.

Suppose that we could see a group of galaxies 9000 million light-years off? We would then be looking backward in time to the extent of 9000 million years, and on the evolutionary theory this is just about the period when the galaxies started to form. In consequence, the appearance would be very different from that of another group of objects closer at hand.

Quite apart from physical appearance, there is distribution to be considered. On the steady-state 'continuous creation' theory, the average amount of matter in any given volume of space has always been much the same, so that if we look back in time for thousands of millions of years we will find conditions just the same as those in our own particular corner of the universe. Not so on the evolutionary theory. Thousands of millions of years ago, the galaxies were closer together than they are now, because expansion had barely begun; in consequence very remote galaxies will appear more crowded together, because we are seeing them as they used to be in the distant past when the whole universe was young.

This should be the acid test. If the most distant galaxies are closer together than expected, the evolutionary theory is right; if not, then the steady-state astronomers win the day. The immediate trouble is that even the 200-inch Palomar reflector is unable to reach out far enough to give us a definite decision, since its 2000 million light-years is not enough.

The cry of 'Build bigger telescopes!' may not provide a satisfactory answer. The Russian 236-inch will help, when completed, but even so it will be inadequate. Optical astronomers are hopelessly handicapped by the atmosphere, which absorbs and distorts visual radiation, so that the only solution is to build a telescope beyond the mantle of air—either out in space or upon a world such as the Moon. This is a tremendous undertaking, and though it will almost certainly be achieved one day it still lies in the indefinite future.

Luckily, radio astronomy comes to our help, and holds out real promise of clearing up the whole problem.

We have seen that radio sources are of various types, from near-by objects such as the Sun and Jupiter to old supernovæ and inter-stellar hydrogen. Radio waves have also been detected from external galaxies, including M.31; another is M.87, an elliptical galaxy in Virgo, which shows an extraordinary 'jet' projecting from the nucleus. Much more interesting from the cosmological point of view is Cygnus A, one of the most intense sources known, which was first detected in the relatively early days of radio astronomy. Here we have a feature far beyond our own Galaxy, and far beyond the comparatively local systems such as M.31. Its distance is estimated at 200 million light-years, and it is not one object—but two. Cygnus A consists of two galaxies which are colliding, and are passing through each other at a speed of something like 1000 kilometres per second.

The idea of two galaxies in collision conjures up a picture of a super-inferno, with stars blazing up as they hit each other and the whole scene enveloped in a glare of radiation. Actually, this is a long way from the truth. Even in the most crowded parts of the universe, stars are a long way apart, and a head-on collision must be very rare indeed. The best analogy is probably that of two orderly crowds moving in opposite directions, and moving through each other. If the men are reasonably spaced out, they will very seldom meet face to face, even if they do not deliberately alter course to avoid knocking against each other, and they will emerge from the encounter quite unhurt even if they are running instead of walking. It is much the same with the stars.

However, many galaxies include a tremendous amount of dust and gas spread thinly between the individual stars. This material will be in collision frequently all the time that the encounter lasts, and here we have the probable origin of our radio waves, even though the exact mechanism is not yet properly understood.

Cygnus A is a perfect example. In a way, we are witnessing a celestial catastrophe; but it is not a catastrophe in the sense that it will have dire results for the galaxies involved.

Just as optical light shows a Doppler shift depending on the approach or recession, so do radio waves. British workers have studied Cygnus A very closely, and have found that the radio Doppler shifts agree excellently with visual ones.

Cygnus A is a faint object in ordinary telescopes. It can be detected and photographed, but it would have aroused no interest among astronomers had it not been a radio source—and nobody could have guessed at its true composite nature. Several other cases are known, notably N.G.C. 5128 Centauri, which shows up as an elliptical galaxy crossed by a dark band; the band seems to be due to dust in the disk of a spiral galaxy which is in collision with the elliptical system. Moreover, collisions seem to be of various types. Some are 'head-on', while others are partial encounters either just beginning or very nearly over. Of course, the whole process of a collision is a very long-drawn-out affair.

If Cygnus A lay at ten times its actual distance, it would be 2000 million light-years away, which is about the real distance of the Hydra cluster of galaxies. Optically, Cygnus A would then be beyond the range of the Palomar reflector, but its radio emission would still be detectable. In fact, radio astronomy can reach out farther than optical astronomy, and by building more efficient radio telescopes we can extend our range.

Remember that on the evolutionary theory, very remote galaxies will seem closer-packed than nearer ones, while on the steady-state theory there will be no difference. This will also affect the number of collisions. Galaxies in clusters will collide reasonably often on the cosmic scale, and if the collision frequency 'increases with distance' it will support the evolutionary picture.

It may well be that before we are able to build a vast optical reflector in space or on the Moon, improved radio techniques will have extended our range out to the vital 9000 million light-years or so. In that case we may be able to decide whether the great clock of the universe is running down or not. We need not even reach the full distance; before then, we will have indications which will lead us to a reliable conclusion, though each problem solved raises such a host of others that even now we are still groping like blind men in an unfamiliar house.

We have found that the Earth is an insignificant body in our Solar System. The Sun has proved to be equally minor in the universe as a whole, and it will be a fitting conclusion if we imagine that we can travel at will through space and see how unimportant we really are.

We begin at the Moon, a mere quarter of a million miles away. Here the Sun is glorious indeed, dominating the sky during the fortnight-long 'day'; at night the Earth is magnificent, casting a strong light across the bleak lunar rocks. But when we travel out to Mars, we find a different picture. The Sun is still dominant, though shrunken in size, but the Earth has become nothing more than a bright starlike object, while the Moon is a mere point of light. Suppose we go to Pluto, more than 3000 million miles away? We lose the Earth; it will seem so close to the Sun, and will be so overpowered by the solar glare, that no telescope equivalent to the Palomar 200 inch will have a hope of showing it, and even the Sun will appear as little more than a small, though still intensely brilliant, source of illumination.

We leave the Solar System, and journey in imagination to Alpha Centauri, the glorious southern binary. From there we find that the constellation patterns are different, though the outer galaxies such as M.31 appear sensibly unaltered in form. The Sun is still visible, shining as an ordinary star of moderate brightness, but the Earth has faded into the distance. If there are astronomers living on a planet which moves round Alpha Centauri, they will require vast telescopes indeed if they are to detect our puny world.

We are still near home, so let us travel on to Rigel, more than 500 light-years away. Now we need a powerful telescope to show us the Sun, which will appear in its true guise of a dim yellow dwarf with no features of outstanding interest. Even the planet Jupiter, giant of the Solar System and big enough to swallow over 1300 Earths, will be almost impossible to detect from the distance of Rigel. Farther away still—in the globular cluster M.13 Herculis, for example—even the Sun will have disappeared; of course, instruments of sufficient power would show it, but they would have to be better than anything which Earth science of the twentieth century can manage.

Beyond the Milky Way? M.31 is the nearest of the really large galaxies, and an astronomer there will see our own system as a faint patch of light in his sky. If he has telescopes he will be able to make out the nucleus and spiral arms, as well as supergiants and Cepheid variables, so that he will be able to draw up a distance scale just as we have done; but the Sun is no supergiant, and will remain unknown in the same way as the millions of other dwarf stars of its kind.

Farther still, the supergiants and Cepheids will fade into the general blur of light, and the spiral form too will vanish, until at last nothing will remain but a hazy dot. If we go to a still greater distance, our great Galaxy, with its host of members, will become so faint that it will be beyond observational range. There is every chance that somewhere in the Hydra cluster of galaxies, an astronomer is at this moment measuring a photographic plate and puzzling as to the significance of a series of patches which mark the Milky Way, M.31, and all the other members of our group. To him, they will be receding just as quickly as the Hydra cluster seems to recede from us.

I have said that 'there is every chance' of such an astronomer living on a planet somewhere in the Hydra cluster of galaxies. This seems to me to be a reasonable statement, though it is unproved and may well be unprovable. Now that we know our true status, why should we suppose that *homo sapiens* is either particularly advanced or particularly rare? Such an idea is as illogical and conceited as the old notion that the Earth lies in the centre of the cosmos.

Look at it from a statistical point of view. The Sun is a normal star, one of perhaps 100 thousand million such stars contained in the Galaxy. The Palomar reflector can reveal 1000 million galaxies of comparable size, so that at a rough estimate, the number of stars definitely known to us is 100 thousand million multiplied by 1000 million—and even then we are dealing with only one part of the universe. In all this multitude, it is folly to suppose that the Sun alone is accompanied by a system of planets; and if such systems are common, there should be millions of worlds where conditions are suitable for life. Modern science also indicates that where life is possible, life will develop, and will assume a form suitable to its environment; the planet Mars, for instance, is capable of supporting low-type vegetation, and this is what seems to have appeared there. If conditions on a far-off planet of another sun favour intelligent life, then presumably it will develop. Whether or not these beings will be physically like ourselves is a matter for debate.

Travel to the stars is fantasy so far as we of 1960 are concerned, and it may well be that interstellar travel is permanently out of the question. This is a pity, since other beings, if we could contact them, might have much to teach us. They may have solved some or all of the problems which confront us—including perhaps the greatest of all: the problem of the creation.

We ourselves may find out some day, if we come to our senses in time; but we still have a long way to go.

Appendices

I

USEFUL WORK FOR THE AMATEUR

There are some fields of astronomical research in which the amateur using relatively modest equipment may still make himself useful. This is particularly the case with regard to physical observations of the Moon and planets; our knowledge of the surface features of Jupiter, for example, depends largely on amateur work, and a 12-inch reflector is quite powerful enough for its owner to participate in the whole programme. Indeed, valuable results may be obtained with apertures smaller than this.

There are fewer opportunities in stellar astronomy, and it is only logical to take a realistic view of the situation. Studies of remote galaxies, for instance, need equipment far beyond the means of any but official bodies; no amateur can hope to contribute, and to carry out spectroscopic work usefully is also more or less impossible. Admittedly, some amateurs have built spectro-helioscopes and other instruments for studying the Sun and have made major contributions with them, but the knowledge required is very great—and so is the expense!

Occasionally it falls to the lot of an amateur to make a spectacular discovery, such as that of a nova. This was the experience of J. P. M. Prentice in 1934, when he was the first to detect DQ Herculis. Unfortunately the chances are very slight, and if you see an object which you cannot identify on your star maps do not be in too much of a hurry to telephone the nearest observatory. 'Novæ' reported to me in this way during the past few years include such un-stellar objects as clouds, aeroplanes, meteorological balloons, and the planets Mars and Saturn.

There are two lines along which really valuable work can be conducted. The separations and position angles of binary stars may be measured, and since many of the published lists are out of date—remember, the components of a binary star reveal perceptible motion if the period is not too long—this would be a real contribution; moreover, it has been neglected of late. A powerful telescope, with accessories such as clock drive and micrometrical equipment, is essential.

More promising, perhaps, is the study of variable stars. The Cepheids can be ruled out; they are closely studied at official observatories, in view of their value as 'standard candles', and their periods are so regular and are known with such precision that there is no point in the amateur's studying them further. This also applies, in the main, to eclipsing binaries. The long-period stars are in a different category altogether. They are not perfectly regular, and they are not nearly so valuable for distance estimates, since there is no set period-luminosity law. This means that professional observers do not spend so much time in studying them, and the amateur has plenty of scope. The irregulars are even more interesting, since one never knows what they are going to do next.

A 6-inch telescope will provide a good observer with plenty of suitable stars which need attention; even a 3-inch is not to be despised, and with a 12-inch there are so many available stars that to cover them all would be very difficult for a lone observer. Work of this sort is carried out by societies such as the British Astronomical Association and the American Association of Variable Star Observers, and recruits are always most welcome. Here, as always, practice makes perfect; after a period of apprenticeship it will be found that accurate estimates can be made, and our knowledge of the stars under watch will increase accordingly. From all points of view, variable star work is the most profitable field of investigation open to the enthusiast whose main interest is in stellar astronomy.

Amateur work in radio astronomy is a real possibility, as has been shown during the last year or two, but is beyond the scope of the present book.

2

THE CONSTELLATIONS

LATIN NAME	ENGLISH NAME	LEADING STAR(S)	REMARKS
Andromeda ..	Andromeda	*Alpheratz*	
Antlia	The Airpump		V. low in Britain.
Apus (=*Avis Indica*)	The Bird of Paradise		Invisible in Britain.
Aquarius	The Water-bearer		Zodiacal.
Aquila	The Eagle	*Altair*	
Ara	The Altar		Invisible in Britain.
Argo Navis ..	The Ship Argo	*Canopus*	Mainly invisible in Britain.
Aries	The Ram	*Hamal*	Zodiacal.
Auriga	The Charioteer	*Capella*	
Boötes	The Herdsman	*Arcturus*	
Cælum	The Sculptor's Tools		V. low in Britain.
Camelopardus ..	The Giraffe		
Cancer	The Crab		Zodiacal.
Canes Venatici ..	The Hunting Dogs		
Canis Major ..	The Great Dog	*Sirius*	
Canis Minor ..	The Little Dog	*Procyon*	
Capricornus ..	The Sea-Goat		Zodiacal.
Cassiopeia ..	Cassiopeia		
Centaurus ..	The Centaur	*Alpha Centauri, Agena*	Invisible in Britain.
Cepheus	Cepheus		
Cetus	The Whale		
Chamæleon ..	The Chameleon		Invisible in Britain.
Circinus	The Compasses		Invisible in Britain.
Columba	The Dove		Low in Britain.
Coma Berenices ..	Berenice's Hair		
Corona Australis	The Southern Crown		Invisible in Britain.
Corona Borealis ..	The Northern Crown	*Alphekka*	
Corvus	The Crow		
Crater	The Cup		
Crux Australis ..	The Southern Cross	*Acrux, Beta Crucis*	Invisible in Britain.
Cygnus	The Swan	*Deneb*	
Delphinus ..	The Dolphin		
Dorado	The Swordfish		Invisible in Britain.
Draco	The Dragon		
Equuleus	The Little Horse		
Eridanus	The River	*Achernar*	Largely invisible in Britain.
Fornax	The Furnace		V. low in Britain.
Gemini	The Twins	*Castor, Pollux*	Zodiacal.

LATIN NAME	ENGLISH NAME	LEADING STAR(S)	REMARKS
Grus	The Crane	*Alnair*	Invisible in Britain.
Hercules ..	Hercules		
Horologium ..	The Clock		Invisible in Britain.
Hydra	The Watersnake	*Alphard*	
Hydrus	The Little Snake		Invisible in Britain.
Indus	The Indian		Invisible in Britain.
Lacerta	The Lizard		
Leo	The Lion	*Regulus*	Zodiacal.
Leo Minor ..	The Little Lion		
Lepus	The Hare		
Libra	The Balance		Zodiacal.
Lupus	The Wolf		Invisible in Britain.
Lynx	The Lynx		
Lyra	The Lyre	*Vega*	
Mensa	The Table		Invisible in Britain.
Microscopium ..	The Microscope		Partly invisible in Britain.
Monoceros ..	The Unicorn		
Musca Australis	The Southern Fly		Invisible in Britain.
Norma	The Rule		Invisible in Britain.
Octans	The Octant		South Polar group.
Ophiuchus ..	The Serpent-bearer	*Rasalhague*	
Orion	Orion	*Betelgeux, Rigel*	
Pavo	The Peacock		Invisible in Britain.
Pegasus	The Flying Horse		
Perseus	Perseus	*Mirphak*	
Phœnix	The Phœnix	*Ankaa*	Invisible in Britain.
Pisces	The Fishes		Zodiacal.
Piscis Australis ..	The Southern Fish	*Fomalhaut*	
Pyxis Nautica ..	The Mariner's Compass		Low in Britain.
Reticulum ..	The Net		Invisible in Britain.
Sagitta	The Arrow		
Sagittarius ..	The Archer		Zodiacal.
Scorpio	The Scorpion	*Antares*	Zodiacal.
Sculptor	The Sculptor		Low in Britain.
Scutum	The Shield		
Serpens	The Serpent		
Sextans	The Sextant		
Taurus	The Bull	*Aldebaran*	Zodiacal.
Telescopium ..	The Telescope		Invisible in Britain.
Triangulum ..	The Triangle		
Triangulum Australe	The Southern Triangle		Invisible in Britain.
Tucana	The Toucan		Invisible in Britain.
Ursa Major ..	The Great Bear		Contains the Plough.
Ursa Minor ..	The Little Bear	*Polaris*	North Polar group.
Virgo	The Virgin	*Spica*	Zodiacal.
Volans	The Flying Fish		Invisible in Britain.
Vulpecula	The Fox		

Argo has been divided up into Carina (the Keel), Vela (the Sails) and Puppis (the Poop). Puppis is partly visible in Britain. Canopus and the strange variable Eta Argûs lie in Carina.

A few constellations have alternative names (Scorpio = Scorpius; Ophiuchus = Serpentarius) and many of the old names have been conventionally shortened (Vulpecula et Anser = the Fox and Goose, has become simply Vulpecula, and there are numerous other examples).

3

THE BRIGHTEST STARS

The following is a list of the 21 apparently brightest stars in the sky. For doubles, such as Alpha Centauri, the combined magnitude is given, but data such as spectrum type refer to the brighter component. The distances and luminosities of some very remote stars, such as Canopus, are hard to define, and different authorities give different values.

STAR	PROPER NAME	R.A. h. m.	DECL. ° ′	MAGNITUDE	SPECTRUM	DISTANCE, LIGHT-YEARS	LUMINOSITY, SUN = 1
α *Canis Majoris* ..	*Sirius*	06 42·9	−16 39	−1·43	A1	8·6	26
α *Argus*	*Canopus*	06 22·8	−52 40	−0·73	F0	650	80,000
α *Centauri*	—	14 36·5	−60 38	−0·27	G2	4	1·1
α *Boötis*	*Arcturus*	14 13·4	+19 26	−0·06	K2	41	100
α *Lyræ*	*Vega*	18 35·2	+38 44	0·04	A0	26	50
α *Aurigæ*	*Capella*	05 13·0	+45 57	0·09	G0	47	150
β *Orionis*	*Rigel*	05 12·1	−08 15	0·15	B8	540	18,000
α *Canis Minoris* ..	*Procyon*	07 36·7	+05 21	0·37	F5	10	5
α *Eridani*	*Achernar*	01 35·9	−57 29	0·53	B3	66	200
α *Orionis*	*Betelgeux*	05 52·5	+07 24	var.	M2	190	1200
β *Centauri*	*Agena*	14 00·3	−60 08	0 66	B0	300	3000
α *Aquilæ*	*Altair*	19 48·3	+08 44	0·80	A7	16	9
α *Tauri*	*Aldebaran*	04 33·0	+16 25	0·85	K5	57	90
α *Crucis*	*Acrux*	12 23·8	−62 49	0·87	B0	230	1000
α *Scorpionis* ..	*Antares*	16 26·4	−26 19	0·98	M1	360	3400
α *Virginis*	*Spica*	13 22·6	−10 54	1·00	B1	230	1500
α *Piscis Australis* ..	*Fomalhaut*	22 54·9	−29 53	1·16	A3	24	13
β *Geminorum* ..	*Pollux*	07 42·3	+28 09	1·16	K0	32	28
α *Cygni*	*Deneb*	20 39·7	+45 06	1·26	A2	650	10,000
β *Crucis*	—	12 44·8	−59 25	1·31	B0	200	850
α *Leonis*	*Regulus*	10 05·7	+12 14	1·36	B7	56	70

4

SOME INTERESTING DOUBLE STARS

The following list is very incomplete, but includes some of the more interesting pairs visible with small telescopes. As elsewhere in this Appendix, the positions are given for epoch 1950.

STAR	R.A. h. m.	DECL. ° ′	MAGNITUDES	POSITION ANGLE, °	DISTANCE ″	REMARKS
Beta Tucanæ	00 29·3	−63 14	4·5, 4·5	170	27·1	
Eta Cassiopeiæ	00 46·1	+57 33	3·7, 7·4	278	8·7	
Beta Phœnicis	01 03·9	−46 39	4·1, 4·2	350	1·3	
Zeta Phœnicis	01 06·3	−55 31	4·1, 8·4	245	6·8	
Zeta Piscium	01 11·1	+07 19	4·2, 5·3	063	23·6	
Alpha Ursæ Minoris ..	01 48·8	+89 02	2·1, 9·0	217	18·3	Polaris.
Gamma Arietis ..	01 50·8	+19 03	4·4, 4·4	000	8·4	Splendid, easy double.
Alpha Piscium ..	01 59·4	+02 31	4·3, 5·2	306	2·5	
Gamma Andromedæ ..	02 00·8	+42 06	2·9, 5·0	061	9·7	Fainter component is again double.
66 Ceti	02 10·2	−02 38	5·9, 7·8	232	16·3	Yellow and blue. Close to Mira Ceti.
Gamma Ceti	02 40·7	+03 02	3·7, 6·2	293	3·0	
Iota Cassiopeiæ ..	02 24·9	+67 11	4·2, 7·1, 8·1	215, 113	2·4, 7·4	Fine triple star.
Eta Persei	02 47·0	+55 41	4·0, 8·5	301	28·4	
Epsilon Arietis	02 56·4	+21 08	6·0, 6·4	205	1·5	
Theta Eridani	02 56·4	−40 30	3·4, 4·4	087	8·2	
Epsilon Persei	03 54·5	+39 52	3·1, 8·3	010	9·0	
Alpha Tauri	04 33·0	+16 25	0·9, 11·1	034	121	Aldebaran. Wide optical double.
Beta Orionis	05 12·1	−08 15	0·1, 6·7	202	9·4	Rigel.

(continued overleaf)

SOME INTERESTING DOUBLE STARS (*continued*)

STAR	R.A. h. m.	DECL. ° ′	MAGNITUDES	POSITION ANGLE, °	DISTANCE ″	REMARKS
Eta Orionis	05 22·0	−02 26	3·8, 4·8	079	1·4	
Beta Leporis	05 26·1	−20 48	3·1, 9·6	313	2·5	
Delta Orionis	05 29·4	−00 20	var., 6·8	000	52·8	
Alpha Leporis	05 30·5	−17 31	4·0, 9·5	156	35·5	
Lambda Orionis	05 32·4	+09 54	4·0, 5·9	043	4·2	
Iota Orionis	05 33·0	−05 56	3·2, 7·3	141	11·4	
Theta Orionis	05 33·0	−05 27	6·0, 7·0, 7·5, 8·0		—	The Trapezium. Superb multiple star.
Sigma Orionis	05 36·2	−02 36	4·0, 10·0, 7·0, 7·5		—	Another superb multiple.
Zeta Orionis	05 38·2	−01 57	1·9, 5·0	159	2·8	
Theta Aurigæ	05 56·3	+37 13	2·7, 7·3	332	2·8	
Gamma Volantis	07 09·2	−70 25	3·9, 5·8	299	13·7	
Lambda Geminorum	07 15·2	+16 38	3·2, 10·2	033	9·9	
Delta Geminorum	07 17·1	+22 05	3·2, 8·2	211	6·7	
Alpha Geminorum	07 31·4	+32 00	1·9, 2·8	204	3·9	Castor; actually a complex multiple.
Kappa Geminorum	07 41·4	+24 31	4·0, 8·5	236	6·8	
Zeta Volantis	07 42·3	−72 29	3·9, 8·9	116	16·7	
Zeta Cancri	08 09·3	+17 48	5·0, 5·7	108	1·1	Fine binary; period 60 years.
Delta Argûs	08 43·3	−54 31	1·9, 6·6	160	3·0	In Vela.
Iota Cancri	08 43·7	+28 57	4·4, 6·5	307	30·7	
Epsilon Hydræ	08 44·2	+06 36	3·9, 7·8	253	3·6	
Upsilon Argûs	09 45·9	−64 50	3·2, 6·0	128	5·0	In Carina.
Gamma Leonis	10 17·2	+20 06	2·3, 3·8	116	3·7	Fine binary; period 407 years.
Xi Ursæ Majoris	11 15·6	+31 50	4·4, 4·9	292	1·9	
Iota Leonis	11 21·3	+10 48	3·9, 7·1	015	0·7	
Beta Hydræ	11 50·4	−33 38	4·4, 4·8	000	1·2	
Alpha Crucis	12 23·7	−62 49	1·4, 1·9	119	4·7	Acrux.

STAR	R.A. h. m.	DECL. ° ′	MAGNITUDES	POSITION ANGLE, °	DISTANCE ″	REMARKS
Delta Corvi	12 27·3	−16 15	3·0, 8·5	212	24·2	
Gamma Centauri ..	12 38·8	−48 41	3·1, 3·1	023	0·5	
Gamma Virginis ..	12 39·1	−01 10	3·7, 3·7	317	5·5	Superb binary; now gradually closing up.
Beta Muscæ	12 43·2	−67 49	3·9, 4·2	004	1·5	
Alpha Canum Venaticic	12 53·7	+38 35	3·1, 5·7	228	19·7	
Theta Virginis	13 07·4	−05 16	4·0, 8·9	343	7·2	
Zeta Ursæ Majoris ..	13 21·9	+55 11	2·2, 4·2	150	14·5	Mizar. In low-power field with Alcor.
Kappa Boötis	14 11·7	+52 01	5·0, 7·2	237	13·2	
Iota Boötis	14 14·4	+51 36	4·9, 7·5	033	38·4	
Alpha Centauri ..	14 36·6	−60 38	0·0, 1·7	310	4·0	Superb binary; period 80 years.
Alpha Circini	14 38·5	−64 45	3·4, 8·8	235	15·8	
Zeta Boötis	14 38·8	+13 57	4·3, 4·8	133	1·1	
Epsilon Boötis ..	14 42·8	+27 17	3·0, 6·3	334	2·8	Fine pair.
Delta Boötis	15 13·5	+33 30	3·2, 7·4	079	105	
Eta Coronæ Borealis ..	15 21·1	+30 28	5·2, 5·7	280	1·0	
Delta Serpentis ..	15 32·4	+10 42	3·0, 4·0	181	3·6	
Zeta Coronæ Borealis ..	15 37·5	+36 48	4·0, 5·9	304	6·3	
Beta Scorpionis.. ..	16 02·5	−19 40	3·0, 5·2	023	13·8	
Alpha Scorpionis ..	16 26·4	−26 19	0·9, 6·8	275	3·0	Antares. Red and greenish.
Zeta Herculis	16 39·4	+31 41	3·0, 6·5	240	1·6	
Mu Draconis	17 04·3	+54 32	5·0, 5·1	102	2·3	
Alpha Herculis ..	17 12·4	+14 27	var., 6·1	112	4·4	Rasalgethi. Red and greenish.
Delta Herculis	17 13·0	+24 54	3·1, 7·5	208	11·0	
Nu Draconis	17 31·2	+55 13	4·6, 4·6	312	62·0	Naked-eye pair.
Alpha Lyræ	18 35·2	+38 44	0·0, 10·5	169	56·6	Vega. Optical double.
Epsilon[1] Lyræ	18 42·7	+39 37	4·6, 6·3	005	2·9	Naked-eye pair with Epsilon[2], at 208″.
Epsilon[2] Lyræ	18 42·7	+39 34	4·9, 5·2	111	2·3	

(*continued overleaf*)

SOME INTERESTING DOUBLE STARS (*continued*)

STAR	R.A. h. m.	DECL. ° ′	MAGNITUDES	POSITION ANGLE, °	DISTANCE ″	REMARKS
Zeta Lyræ	18 43·0	+37 33	4·2, 5·5	150	43·7	
Theta Serpentis ..	18 53·7	+04 08	4·1, 4·1	103	22·3	Magnificent pair of 'twins'.
Eta Lyræ	19 12·0	+39 03	4·0, 8·0	083	28·2	
Beta Cygni	19 28·7	+27 51	3·0, 5·3	055	34·6	Albireo. Yellow and bluish. Superb.
Delta Cygni	19 43·5	+45 00	3·0, 7·9	263	1·9	
Epsilon Draconis ..	19 48·3	+70 08	4·0, 7·6	009	3·3	
Alpha Capricorni ..	20 14·9	−12 40	3·2, 4·2	291	376	Naked-eye pair.
Gamma Delphini ..	20 44·4	+15 57	4·0, 5·0	270	10·5	
Beta Cephei	21 28·0	+70 20	3·4, 8·0	250	13·7	
Kappa Pegasi	21 42·4	+25 25	3·9, 10·9	296	12·9	
Zeta Aquarii	22 26·2	−00 17	4·4, 4·6	291	2·6	
Delta Cephei	22 27·3	+58 10	var., 7·5	192	41·0	

5

SOME INTERESTING VARIABLE STARS

Again this list is very incomplete, and is confined to variables which at maximum exceed magnitude 6·0. Periods for stars of the Mira type are general averages, and the average spectrum type is given.

STAR	R.A. h. m.	DECL. ° ′	MAGNITUDE MAX.	MAGNITUDE MIN.	SPECTRUM	TYPE	PERIOD DAYS	REMARKS
T Ceti	00 19·2	−20 20	5·1	7·0	M	Irregular	—	
R Andromedæ ..	00 21·4	+38 18	5·6	15	M	Long-period	410	
Alpha Cassiopeiæ..	00 37·6	+56 15	2·1	2·5	K	Irregular	—	Variability questioned.
Gamma Cassiopeiæ	00 49·5	+60 04	1·6	3·4	Peculiar	Pseudo-nova	—	
Omicron Ceti ..	02 16·8	−03 12	1·6	9·6	M	Long-period	331	Mira.
R Trianguli ..	02 34·0	+34 03	5·8	12	M	Long-period	270	
Rho Persei ..	03 02·0	+38 39	3·3	4·1	M	Irregular	—	
Beta Persei.. ..	03 04·9	+40 46	2·3	3·5	B	Eclipsing	2·87	Algol.
Lambda Tauri ..	03 57·8	+12 20	3·3	4·2	B	Eclipsing	3·9	Algol type.
R Doradus ..	04 36·3	−62 10	5·7	6·8	M	Long-period	360	
Epsilon Aurigæ ..	04 58·4	+43 44	3·3	4·1	F	Eclipsing	27·5 *yrs.*	
Alpha Orionis ..	05 52·5	+07 24	0·1	1·3	M	Irregular	—	Betelgeux.
U Orionis ..	05 52·9	+20 11	5·4	12	M	Long-period	374	
Eta Geminorum ..	06 11·9	+22 31	3·2	4·2	M	Long-period	231	Unusual type.
T Monocerotis ..	06 22·5	+07 07	5·8	6·8	G	Cepheid	27·0	
Zeta Geminorum ..	07 01·2	+20 39	3·7	4·3	G	Cepheid	10·2	
R Geminorum ..	07 04·3	+22 48	5·9	14	G	Long-period	370	
R Canis Majoris ..	07 17·2	−16 18	5·9	6·7	F	*Eclipsing*	*1·14*	*Algol type.*

(continued overleaf)

SOME INTERESTING VARIABLE STARS (*continued*)

STAR	R.A. h. m.	DECL. ° ′	MAGNITUDE MAX.	MAGNITUDE MIN.	SPECTRUM	TYPE	PERIOD DAYS	REMARKS
V Puppis	07 56·7	−49 06	4·1	4·9	B	Eclipsing	1·45	Beta Lyræ type.
R Carinæ	09 31·0	−62 34	4·5	10	M	Long-period	309	
l Carinæ	09 43·9	−62 17	3·6	5·0	G	Cepheid	35·5	
R Leonis	09 44·9	+11 40	4·9	10·5	M	Long-period	312	
S Carinæ	10 07·8	−61 19	5·8	9·0	M	Long-period	149	
U Hydræ	10 35·1	−13 07	4·5	6·0	N	Irregular	—	
Eta Argûs	10 43·0	−59 25	−1·1	7·8	Peculiar	Pseudo-nova	—	
T Ursæ Majoris	12 34·1	+59 46	5·5	13	M	Long-period	254	
R Hydræ	13 26·9	−23 01	4·0	10	M	Long-period	415	
S Virginis	13 30·4	−06 56	5·6	12·5	M	Long-period	372	
T Centauri	13 38·9	−33 21	5·2	10	M	Long-period	90	
Theta Apodis	14 00·5	−76 33	5·1	6·6	M	Irregular	—	
R Centauri	14 13·0	−59 41	5·3	13	M	Long-period	560	
W Boötis	14 41·2	+26 44	5·2	6·1	K	Irregular	—	
Delta Libræ	14 58·3	−08 19	4·8	6·2	A	Eclipsing	2·05	Algol type.
R Coronæ Borealis	15 46·4	+28 19	5·8	12·5	Peculiar	Irregular	—	
R Serpentis	15 48·4	+15 17	5·5	13·4	M	Long-period	357	
T Coronæ Borealis	15 57·4	+26 04	1·9	9·5	Peculiar	Recurrent nova	—	
g Herculis	16 27·0	+41 59	4·7	6·0	M	Irregular	—	
S Herculis	16 49·7	+15 02	5·9	12·5	M	Long-period	300	
R Scorpionis	16 53·4	−30 30	5·6	11·3	M	Long-period	279	
Alpha Herculis	17 12·4	+14 27	3·1	3·9	M	Irregular	—	Rasalgethi.
U Ophiuchi	17 14·0	+01 16	5·7	6·7	B	Eclipsing	1·68	Algol type.
u Herculis	17 15·5	+33 09	4·8	5·4	B	Eclipsing	2·05	Beta Lyræ type.
X Sagittarii	17 44·5	−27 49	4·3	5·0	F	Cepheid	7·01	
W Sagittarii	18 01·8	−29 35	4·8	5·8	F	Cepheid	7·59	

STAR	R.A. h. m.	DECL. ° ′	MAGNITUDE MAX.	MIN.	SPECTRUM	TYPE	PERIOD DAYS	REMARKS
Y Sagittarii ..	18 18·5	–18 53	5·4	6·5	G	Cepheid	5·77	
R Scuti	18 44·9	–05 46	4·7	7·8	G	Irregular	—	
Beta Lyræ	18 48·2	+33 18	3·4	4·1	B	Eclipsing	12·91	Prototype star.
R Lyræ	18 53·9	+43 53	4·0	4·7	M	Irregular	—	
Kappa Pavonis ..	18 51·8	–67 18	4·0	5·5	F	Cepheid	9·10	
R Aquilæ	19 04·0	+08 09	5·8	12	M	Long-period	310	
Chi Cygni ..	19 48·6	+32 48	4·2	14	M	Long-period	409	
Eta Aquilæ ..	19 50·0	+00 53	3·7	4·5	G	Cepheid	7·18	
S Sagittæ	19 53·8	+16 30	5·4	6·1	G	Cepheid	8·38	
T Vulpeculæ ..	20 49·3	+28 03	5·2	6·4	F	Cepheid	4·44	
W Cygni	21 34·1	+45 09	5·0	6·7	M	Long-period	132	
Mu Cephei ..	21 41·9	+58 33	3·7	5·7	M	Irregular	—	Herschel's 'Garnet Star'.
Delta Cephei ..	22 27·3	+58 10	3·6	4·3	G	Cepheid	5·37	The prototype Cepheid.
Beta Pegasi ..	23 01·3	+27 48	2·2	2·8	M	Irregular	—	Rough period ± 30 days
R Cassiopeiæ ..	23 55·8	+51 07	5·3	12	M	Long-period	432	

Most of these variables are easy to find, and it is worth noting that stars of late type (K and M) are often strongly orange-red in colour. Note also that U Hydræ is the only N-type star ever visible to the naked eye.

6

SOME INTERESTING NEBULAR OBJECTS VISIBLE WITH SMALL TELESCOPES

OBJECT	CONSTELLATION	R.A. h. m.	DECL. ° ′	TYPE	REMARKS
47 Tucanæ	Tucana	00 21·9	−72 22	Globular	Great globular.
M.31	Andromeda	00 40·0	+41 00	Spiral galaxy	Great galaxy.
N.G.C. 362	Tucana	01 00·7	−71 06	Globular	Visible to naked eye.
M.33	Triangulum	01 31·0	+30 24	Spiral galaxy	Faint.
H.IV. 33-34	Perseus	02 19·0	+56 54	Open clusters	Sword-handle.
M.103	Cassiopeia	01 29·8	+60 26	Open cluster	Near Delta.
M.77	Cetus	02 40·1	−00 15	Spiral galaxy	Near Delta.
M.45	Taurus	03 40·0	+23 30	Open cluster	Pleiades.
M.38	Auriga	05 25·3	+35 48	Open cluster	Fine object.
M.1	Taurus	05 31·5	+21 59	Supernova wreck	Crab Nebula.
M.42	Orion	05 32·5	−05 25	Galactic nebula	Sword of Orion.
30 Doradûs	Dorado	05 39·1	−69 09	Gaseous nebula	In Nub. Major
M.37	Auriga	05 49·6	+32 33	Open cluster	Bright cluster.
M.35	Gemini	06 05·7	+24 21	Open cluster	Conspicuous.
M.41	Canis Major	06 44·9	−20 42	Open cluster	Visible to naked eye.
M.46	Argo Navis	07 39·5	−14 22	Open cluster	In Puppis.
M.44	Cancer	08 37·2	+20 10	Open cluster	Præsepe.
M.81	Ursa Major	09 51·5	+69 18	Spiral galaxy	M.82 is nearby.
N.G.C. 3372	Argo Navis	10 43·0	−59 25	Gaseous nebula	Round Eta Argûs.
M.97	Ursa Major	11 11·8	+55 17	Planetary	Owl Nebula.
N.G.C. 3766	Centaurus	11 33·9	−61 20	Open cluster	Bright object.

OBJECT	CONSTELLATION	R.A. h. m.	DECL. ° ′	TYPE	REMARKS
N.G.C. 4755	Crux Australis	12 50·7	−60 05	Open cluster	Jewel-box.
Omega Centauri	Centaurus	13 23·7	−47 03	Globular	Finest globular.
M.51	Canes Venatici	13 27·8	+47 27	Spiral galaxy	Whirlpool.
M.3	Canes Venatici	13 39·9	+28 38	Globular	Easy object.
M.5	Serpens	15 15·9	+02 16	Globular	Easy object.
N.G.C. 6025	Triang. Aust.	15 59·4	−60 21	Open cluster	Bright.
N.G.C. 6067	Norma	16 09·4	−54 05	Open cluster	Large and rich.
M.80	Scorpio	16 14·1	−22 51	Globular	Condensed.
M.13	Hercules	16 39·9	+36 33	Globular	Great globular.
M.19	Ophiuchus	16 59·5	−26 12	Globular	Low in Britain.
M.92	Hercules	17 15·6	+43 12	Globular	Easy object.
M.6	Scorpio	17 36·7	−32 10	Open cluster	'Butterfly'.
M.23	Sagittarius	17 54·0	−19 01	Open cluster	Fine field.
H.IV. 37	Draco	17 58·6	+66 38	Planetary	Central 9m star.
M.8	Sagittarius	18 00·6	−24 23	Galactic nebula	Lagoon Nebula.
N.G.C. 6572	Ophiuchus	18 10·2	+06 50	Planetary	Bright object.
M.17	Sagittarius	18 18·0	−16 12	Galactic nebula	Omega Nebula.
M.22	Sagittarius	18 23·3	−23 57	Globular	Near Sigma.
M.11	Scutum	18 48·2	−06 20	Open cluster	'Wild Duck'.
M.57	Lyra	18 52·0	+32 58	Planetary	Ring Nebula.
M.27	Vulpecula	19 57·4	+22 35	Planetary	Dumb-bell Nebula.
H.IV. 1	Aquarius	21 01·4	−11 34	Planetary	Saturn Nebula.
M.15	Pegasus	21 27·6	+11 57	Globular	Easy object.
M.2	Aquarius	21 30·9	−01 04	Globular	Fine globular.
H.IV. 18	Andromeda	22 23·4	+42 12	Planetary	Easy object.

7

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Index

Index