bodies, one luminous and one dark, which, by their mutual attraction at short distances, formed a peculiar specimen of binary. The observed motion of Sirius was its orbital motion about their common centre. The orbit derived by C. A. F. Peters in 1850 had a period of revolution of 50 years and a half-major axis of 2.4″. Then it happened in 1862 that Alvan Clark, in order to test the quality of his just finished 18 inch objective, had it pointed at Sirius, and that close to it a small speck of light was perceived, hardly visible in the glare of the mighty star. When the discovery was made known and the object was seen also in other telescopes, measurements showed it to stand relative to Sirius exactly in the direction of the centre of the orbit, at a distance two times greater. It was Bessel's dark star. So it was not entirely dark, only very faint, a star of the eighth magnitude, nearly 10,000 times fainter than Sirius. Yet, since it was twice as far from the centre of gravity as Sirius itself, its mass was as much as half the mass of Sirius. Though not a dark star in the strict sense, this Sirius B, as it is called, remains a remarkable object because of this combination of great mass and small luminosity—how remarkable appeared later on. Sirius has since been measured regularly like any other binary. The dark star for Procyon was discovered in 1895, by Schaeberle with the 36 inch Lick telescope, as a still fainter star of the thirteenth magnitude.

Binaries are highly important in astronomy, because they are the only objects showing the effect of attraction, so that only by them can we acquire knowledge of the masses of the stars. The formula deduced by Newton as an extension of Kepler's third law—that the ratio of the cube of the major axis and the square of the period of revolution is proportional to the total mass—can be applied to binaries as soon as the parallax is known. The parallax is needed to derive the major axis in astronomical units from the observed major axis in seconds of arc. For Sirius, half the major axis (7.5″, i.e. being 20 times the parallax 0.37″) is 20 astronomical units; with the period of 50 years, a total mass of $20^3 : 50^2 = 3.2$ times the sun's mass is found. So, in the search for stars interesting for parallax measurements, binaries were preferred. Since for Sirius the distance of the chief star from the centre of gravity was known to be $\frac{1}{3}$ of the distance of the two components, it followed that the separate masses of the components were $\frac{1}{3}$ and $\frac{2}{3}$ of the total amount. The same computation could be made for some other bright binaries when a great number of meridian observations disclosed the motion of the bright component. The masses thus found were no more than 10 times greater or smaller than the sun's mass, though their luminosities may diverge a million times.

A new kind of binary was discovered in photographing stellar spectra. In 1889 Antonia C. Maury at Harvard Observatory perceived that in

the spectrum of ζ Ursae Majoris the K line, the only clearly visible narrow line, sometimes was double, sometimes single; still more regularly the same happened with β Auriga, where the line on successive days was alternately double or single (plate 15). 'Double' means the star has two different radial velocities, i.e. it consists of two components whose spectra shift periodically in opposite directions because they revolve about their centre of gravity. For β Aurigae the period is four days. Such 'spectroscopic binaries' have been found in great numbers; they form a special class, because they can be discovered only when their orbital velocities are large, amounting to tens and hundreds of kilometres per second, whereas their orbits are so small that their duplicity cannot be observed with the largest telescopes.

At the same time, about 1890, Vogel and Scheiner at Potsdam were photographing spectra of bright stars with a new excellent spectrograph, to determine their radial velocities. They perceived that with some stars, such as Spica in Virgo and Algol in Perseus, this velocity periodically increased and decreased. So these stars also were spectroscopic binaries, different from the other kind because the second spectrum was invisible. This does not mean that the other star is dark, but only that it is so much fainter that its absorption lines are blotted out. Spectroscopic binaries of this kind, with single periodically displaced lines, are far more numerous than those with doubling lines. In the following years Campbell at Lick Observatory discovered a large number of them; in his catalogue of 1924 more than one thousand are listed. He estimated that one-third of all stars belong to them; though single stars like our sun form the majority, yet duplicity is a common condition. The theoretical deductions on the division of rapidly rotating bodies and the effect of tidal friction might well be applied here; the wide pairs with periods of hundreds of years, however, can hardly be explained in this way.

The above-mentioned star Algol in Perseus was already renowned in astronomy, because Goodricke in 1782 had discovered its regular variations in brightness; always, after a period of 2 days 22 hours, its light decreases for 4 hours to a minimum and then increases in the same time to its normal constant brightness. Algol was one of the 'variable stars', i.e. variable in brightness, of which a small number had been discovered by chance and observed more or less regularly. A regular, uninterrupted engagement with these objects began with F. W. A. Argelander (1799–1875). He introduced the method of estimating small differences in brightness in 'steps', thus improving Herschel's former method by using numerical values instead of commas and dashes. His first results were published in 1843 in a paper on β Lyrae; and in the following quarter of a century he continued to observe the known and newly-discovered variables, deriving their periods and light curves. In 1844, in an 'Appeal to Friends of Astronomy', he indicated a number of important objects of research for amateurs, which demanded only small instruments or none, and which the astronomers in their observatories had to neglect because their big and expensive instruments had to be used for more difficult objects. Such were twilight, the meteors, zodiacal light, the Milky Way, the brightness and colour of the stars, and especially the variable stars. His appeal and example stimulated many younger people and pupils, like Eduard Heis at Munster, Julius Schmidt, who in Athens worked on all these objects, and Eduard Schönfeld. Besides these, a number of amateurs occupied themselves with variable stars, of which more and more telescopic specimens were discovered owing to the improved star maps. A catalogue, compiled by Chandler in 1889, already enumerated as many as 225 items. The different types known from the eighteenth century by some bright representatives all increased in membership now. In the standard catalogue published in 1919 by Gustav Müller and Ernst Hartwig, there were 131 variables of the Algol type, which, in reality, are common stars occulted now and then by others. The β Lyrae type, regularly varying in mostly small periods between two equal maxima and two unequal minima, numbered 22 stars. The continuously changing stars of short period, called 'Cepheids' after δ Cephei, accounted for 169 items. The largest number, more than 600, were strongly variable red stars with periods of the order of one year, called 'Mira type' after the first discovered 'wonderful star of the Whale'. Furthermore, there are bright red stars rather irregularly oscillating by small amounts, such as α Herculis, already mentioned as discovered by William Herschel, and Betelgeuse, found to be variable by his son, John Herschel, in 1836.

The cause of the variation in brightness in the case of the Algol stars was obvious. Goodricke's explanation of an occultation by a dark satellite star was a plausible hypothesis. It acquired certainty when Vogel and Scheiner in 1889 found that the visible star Algol recedes from us before the minimum, and approaches after the minimum, and hence during minimum is behind the companion. This explanation holds for all the variables of the Algol type, therefore called 'eclipsing variables'. Though belonging to the variable stars according to observational practice, they belong by their nature to the spectroscopic binaries. That their variation is not physically real but the result of a geometrical situation gives them a special importance. With all the other stars, our sun excepted, we must be content with studying their integrated light. We see them as points—by the telescope magnified into spurious discs—not as real discs, so that the different parts cannot

be distinguished. In stellar eclipses, however, one disc gradually covers and uncovers the other; so they are the only stars in which the differences between separate parts of the disc, e.g. centre and edge, can be an object of investigation. The diversity of relative diameter and surface brightness of the components, combined with the situation of the orbit, produces a rich variety in the shapes of the light curve; conversely, these light curves allow the physical and geometrical conditions to be derived. The variable U Cephei, discovered in 1880 by Ceraski at Moscow, which in full light has a magnitude of 6.9, shows a minimum magnitude of 9.2, which remains constant for a couple of hours; hence a small disc enters before or hides behind a large disc. The variable Y Cygni, discovered by Chandler in 1886, had an eclipse every 1½ days, in which it decreased to half the full light. The period at first seemed to be irregular, until in 1891 Dunér at Uppsala found that the interval was alternately smaller and larger; the difference, moreover, gradually decreased and, after passing zero, increased in the opposite direction. He could explain it by two exactly equal stars alternately occulting each other in a period of three days, in an elliptical orbit, in which the major axis revolved rather rapidly. So we have here a perturbation in a stellar system, caused probably by deformation through mutual attraction. Numerous eclipsing variables show two alternating minima of unequal depth, in all intermediate degrees between exact equality and a secondary minimum hardly perceptible if the second star is faint.

Is Algol's dark companion really dark? Several observers tried in vain to detect a secondary minimum, until in 1910 Stebbins succeeded in discovering it by means of his selenium photometer. Its depth was only 0.06 magnitude, corresponding to 6 per cent loss of light.* Here it appears that, for the study of Algol stars, Argelander's method of step estimates is not sufficiently exact to afford values of the brightness suitable to be compared with geometrical theory. Photometric measurements were needed. About 1880 some had been made in Potsdam and at the Harvard Observatory, but only in far too small a number. It was Dugan who, at Princeton Observatory in 1905–10, determined, photometrically, exact light curves for a large number of eclipsing variables, with only a few per cent of uncertainty for each value of the brightness. This accuracy was obtained as the average of extensive series of observations; since all this photometry was based on ascertaining the equality of two stellar images by eyesight, its accuracy depended on the limited power of the eye to detect differences in brightness; this limit is about 5 per cent. Fundamental progress was possible only by substituting a

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* As explained in the next chapter, 0.06 magnitude means a logarithmic decrease of 0.4 × 0.06 = 0.024, which is the logarithm of 1.059.

physical apparatus for the human eye. Stebbins' selenium photometer, in which light produced a change in the electrical resistance, was the first attempt of this kind and was rewarded by the detection of Algol's secondary minimum.

The derivation of the elements of the eclipse—the relative size and brightness of the stars and the dimensions, form and inclination of the orbit—from the shape of the light curve demands very laborious computations. Formulas were derived by Pickering in 1880 and by Myers in 1895. An effective solution of the problem was given in 1912 by Henry Norris Russell of Princeton, in the form of a practical computation scheme based upon a number of auxiliary tables. They were used by Harlow Shapley in 1913 in a careful determination of the geometrical elements for all the eclipsing variables for which Dugan had provided sufficient data. Because the distribution of intensity over the disc was also an unknown element, Shapley computed the other elements under two extreme suppositions: either uniform brightness over the entire disc or its regular decrease to zero at the limb. He found that in both cases all the points of the light curve could be equally well represented. This means that the coefficient of limb darkening could not be found in this way; the light curves computed for both cases (each with its own elements) coincided well-nigh completely and deviated only at a few places by some few hundredths of a magnitude. For this purpose the photometric results were still too coarse; more precise measurements were needed.

Fortunately, a better method had been developed only a few years before. About 1911 the German physicists Elster and Geitel had improved the photoelectric cell into an extremely sensitive instrument for measuring small light intensities. It was soon used for the stars by Guthnick and Prager at Berlin and by Rosenberg in Tübingen and was found to determine the brightness of a star with a ten times greater accuracy than was possible by visual comparisons: the magnitude differences had to be expressed in three decimals, with errors of some thousandths instead of hundredths of a magnitude. This accuracy, not necessary for common stars, was valuable for variable stars—the two Berlin astronomers detected a small variability in hitherto unsuspected stars—and it was just what was needed for the eclipsing variables. At the Lick Observatory Gerald Kron constructed a highly sensitive instrument of this type and in 1937–38 determined the light curve of the Algol star 21 Cassiopeiae with a probable error of not more than 0.002 of a magnitude. Thus he was able to derive the coefficient of limb darkening at 0.58 ±0.04, the first reliable value next to that of our sun.

Eclipsing variables may be useful in still another way. The duration of the eclipse relative to the period determines the dimension of the

stars relative to the size of the orbit. The diameter, to the third power, determines the volume; the radius of the orbit, to the third power, determines the mass; so, together, they determine the mean density of the stars without needing parallaxes or true dimensions.

A sensational case was the third-magnitude star ε Auriga. Since 1843 Julius Schmidt had suspected it of showing small irregular variations. Argelander and Heis in 1847–48 saw it as a fourth-magnitude star; but in the following years it showed doubtful fluctuations only. In 1875 it was again seen to be faint, but only for a short time. When this was repeated in 1901 and a variable radial velocity had been found in the meantime, Ludendorff at Potsdam realized that it was an eclipsing variable of unusual dimensions: it had a period of 27 years, in which the star decreased for seven months, remained constant for ten months and increased in seven months to normal brightness.

The diversity in the phenomena of eclipsing variables is increased still more by variations of the full light between the eclipses in some of them. First, because in the case of a small distance the fainter star, strongly illuminated by the other, increases the total light on both sides of the secondary minimum, and second, because the stars by their mutual attraction are elongated and show their larger surfaces between the eclipses. Such stars form a transition to the β Lyrae type, which, in continuous variation in each period, shows two equal maxima and two unequal minima. Or, expressed in another way, the β Lyrae stars are extreme specimens of eclipsing variables. Periodical variations of radial velocity had indeed been established by Lockyer in 1893 and by Belopolsky at the Pulkovo Observatory in 1892; the components, different in brightness and spectrum, revolve with great velocity (of 155 km.) at so short a distance from each other that they must nearly touch. For β Lyrae, considered as a double star, elements were computed by Myers in 1896 and by Stein in 1907. Yet, with its many curious spectral changes, it remained one of the puzzles of astronomy.

Periodical variations of radial velocity were also established for δ Cephei in 1894 by Belopolsky, and it was soon found to be a property of all these short-period variables. In 1907 Sebastian Albrecht at the Lick Observatory remarked that the light curve and the velocity curve not only coincided in that the most rapid approach took place at maximum brightness, but even their shape was similar in minor details. Nobody at the time had any doubt that these Cepheids were spectroscopic binaries; but there were difficulties. The irregular shape of the light and velocity curves—often a rapid increase and a slow, sometimes interrupted, decrease—was hard to account for, even with a large eccentricity. That the temperature at maximum brightness was also higher than at minimum had been demonstrated by Schwarzschild in

1899 by photographic measurements, which showed a range in brightness $1\frac{1}{2}$ times larger than was observed visually, indicating a colour more blue at maximum than at minimum. Tides produced by the attraction of the companion were invoked, or a heating at the front during rapid motion through a resisting medium was thought to produce the maximum. In this case, however, the resistance would greatly change the period, which, in reality, was almost constant. The moderate orbital velocity combined with a short period demanded, in the case of a binary, a very small mass, less than $\frac{1}{100}$th of the sun's mass. The large size of the star derived from other data meant that the centre of gravity was situated deep in its interior, so that in its motion it would scarcely be justified to distinguish a front.

Then the pulsation theory was advanced; though suggestions along this line had been made by others, it was Shapley who in 1914 exposed and defended it in all its consequences. The alternate approach and recession measured in the spectrograms are the effect of the alternating expansion and contraction of the star. These periodic changes in dimension and volume are adiabatic changes, i.e. the heat needed for or produced by the change of volume is given off or taken up by the stellar gas as decrease (during expansion) or increase (during contraction) of temperature. There is something odd about stars that cannot find their equilibrium but alternate in endless pulsation between too large and too small, too cold and too hot. Yet this explanation for the short-period variables was soon accepted by the astronomical world, especially when Eddington in 1918 had developed a theory of pulsating stars, based upon his researches on the constitution of the stars in general. Yet in this theory, too, there remained difficulties not directly solvable, especially as to why the observed maximal brightness and temperature came, instead of at the moment of smallest volume, at exactly a quarter of a period later, when the star was already rapidly expanding.

With their theoretical importance, the necessity for a more accurate determination of the light curves of the Cepheids was felt. During the entire nineteenth century the light curves had been derived by astronomers and amateurs by means of step estimates following Argelander's example. These, however, could not guarantee a uniform scale over the entire range of variation. Here photometric measurements had to come to the rescue. Since an accuracy of 0.01 magnitude sufficed and 0.001 magnitude was not needed here, visual photometry could be used. Photography also was tried, when methods of photographic photometry developed, especially in connection with the great star-mapping enterprises such as the *Carte du ciel*. On a photographic negative of a field of stars, the size of the black dots varies with the brightness of the stars. Empirical formulae were derived in about 1890 by many astronomers (Charlier, Scheiner, *et al.*) to find stellar magnitudes from measured diameters. It appeared that bad objectives, with much stray light about the stellar images, gave better results (because of the greater diameters) than plates taken with good objectives; but the indefinite borders of the star discs always made it a coarse procedure. It was an important improvement or, rather, an entire renovation of the basis of photographic photometry, when Schwarzschild in 1899, in the above-mentioned research, introduced the use of extra-focal images. By placing the plate at some distance, inside or outside the focus, he obtained, for all the stars, smooth discs of equal size but of different blackness, i.e. density of the silver deposit. Differences in blackness can be distinguished far more accurately than differences in diameter on focal plates (pl. 15).

A Cepheid variable (η Aquilae) was the first object and motive of his method, which has proved most important for this class of variables. In this first research Schwarzschild had to estimate the blackness in a self-made artificial scale of comparison discs. The accuracy was increased when, in the same year, Hartmann at Göttingen had constructed his 'microphotometer' for the measurement of silver densities by equalizing them—in a most exact way, by the disappearance of the border line—to the blackness at some point in a wedge of dark glass. In order to reduce the measured densities to magnitudes, Hertzsprung in 1910 devised how to put a scale on each plate by taking the photographs through a coarse grating placed before the objective. Then diffraction images appear on both sides of the star disc, fainter discs of the same size, of which the ratio of brightness can be computed exactly. Thus the basis was laid for an exact photographic photometry of the stars, and several observatories have since contributed in this way to the derivation of accurate light curves of Cepheids.

The red variables of large period and great amplitude, called the Mira type, remained as the appropriate field for step estimates by Argelander's method. With an extent of variation of 4 to 8 magnitudes, or even to 10, and with the many irregularities in the light variation itself, errors of 0.1 magnitude are irrelevant. Here was a fertile field of work for amateurs with small telescopes, though the greater telescopes of the observatories had to complete the regular record for the faintest minima below the twelfth magnitude. With the increase in the number of objects, the number of workers in this field also increased, and they organized into special societies, in order by co-operation to ascertain the star's behaviour from day to day. A variable radial velocity has also been found in Mira stars, but most important here are the spectral changes, which present many riddles.

The most peculiar among peculiar stars are the new stars, the 'novae'. No innocent, ever repeating, fluctuations here! What they present are catastrophes, alarming man and raising problems of world destiny. Stellar catastrophes stood at the cradle of astronomy—if the tale is true that Hipparchus was induced to make his star catalogue by the appearance of a new star—and were beacon lights in its revolutionary epoch, when the novae of 1572 and 1604 drove Tycho to astronomy and inspired Kepler and Galilei. Then they became scarce; during the entire eighteenth and the first part of the nineteenth centuries, none were mentioned. Was this through lack of attention? Surely there has not been such a display of conspicuous apparitions as that which occurred in the second half of the nineteenth century. It was opened by a modest nova of the fifth magnitude in Ophiuchus, discovered by Hind in 1848. We omit here the star η Carinae in the great nebula of the Ship as forming a separate type; earlier regarded as of the fourth magnitude, it was observed by John Herschel in 1838 as a first-magnitude star; after a relapse, it flared up again in 1843 to a brightness equalling Sirius, and then gradually faded to the sixth magnitude.

In 1866 a second-magnitude nova appeared in the Crown; in 1876 another of the third magnitude in the Swan; in 1892 a fourth-magnitude nova appeared in Auriga; in 1901 a first-magnitude one was found in Perseus; and in later years occurred several of magnitudes 5, 4 or 3, with again a first-magnitude star which appeared in 1918 in Aquila. They all exhibited the same normal, common behaviour: they flared up suddenly, in a single day, to a brightness 10,000 times and more, surpassing their former light; then they began to decrease slowly, sometimes with irregular or periodic variations, until they faded out. Nova Aurigae 1892, as it appeared on Harvard plates taken earlier, had been fluctuating about the fourth magnitude many weeks before its discovery. It suggested to Seeliger the explanation (contrary to the then prevalent opinion of a collision between two stars) that the star was heated by friction during its rapid passage through a nebulous cloud of variable density. Nova Persei in 1901, half a year after its outburst, a faint star already, was seen to be surrounded by a faint nebulous ring at 7″ distance, which slowly expanded. Kapteyn and Seeliger explained it as the glare of the outburst spreading with the velocity of light over the surrounding nebulous masses. Thus it was possible to derive for it a distance of about 200 parsecs.

To be free from the chance discovery or non-discovery by amateurs on the lookout, a 'sky patrol' was installed at the Harvard Observatory, a large-field camera, continually photographing the entire sky every night. Any foreigner can be tracked immediately, and for every newly-discovered nova the previous history can be read afterwards. All the

novae in this way were completely registered; most of them were, of course, telescopic in their greatest brightness. On the basis of these records Bailey estimated that 10 to 20 novae brighter than the ninth magnitude appear yearly. On the conjecture that they are all within a distance of 10,000 parsecs and that the number of stars therein is 10,000 million, it is found that, on the average, each star has a chance to become a nova once in a thousand million years, certainly less than its probable term of life. The possibility that every star—our sun included—once or oftener during its existence should be subjected to an all-destroying fiery blaze provided a new, rather disquieting, aspect for our little world's future. It might be, however, that the conditions for nova outbursts as a kind of instability are present only in special stars; cases are known of repeated outbursts of the same star. Milne, in his general theory of stellar structure, in 1928 also gave a theory of collapsing stars, where inner instability results in a catastrophe. It is clear, however, that only a profound knowledge of the processes in the interior of the stars will shed light on the origin of nova outbursts.

CHAPTER 40

COMMON STARS

THE common stars differ among themselves in apparent brightness—to which fact we owe the picturesque aspect of the starry heavens—and also in colour. Ptolemy had already expressed the differences in brightness by forming six classes, which he called the first to the sixth magnitudes, the last at the limit of visibility. From the number in each of these classes—15, 45, 208, 474, 217 and 49—it is clear that the two faintest classes were very incomplete. The use of the word 'magnitude' for brightness does not mean simply that when a star is bright it is automatically called a big star, but it includes the assumption that bright stars have greater size than faint stars. Tycho Brahe assumed the size of first-magnitude stars to be 2′, of third-magnitude stars 1′. Because the eye easily distinguishes smaller differences in brightness than one magnitude, Ptolemy added to some of the stars the designation 'smaller' or 'larger'.

In the two centuries of revolutionized astronomy the problems of position and motion so engrossed men's minds that little attention was given to brightness. On the celestial maps, in the tradition of antiquity, the human or animal figures of the constellations were prominent, while the stars themselves were often inconspicuous. The transition to a more rational celestial cartography came through the work of Argelander. Moving to Bonn in 1837, he spent the years while the observatory was being built, when he was without instruments, in constructing an atlas which was to depict all the stars visible to the naked eye in their true magnitude as established by careful intercomparisons. In this atlas, published in 1843 and called *Uranometria Nova* (pl. 16), as a modern substitute for Bayer's *Uranometria*, the numbers of the stars for each magnitude from the first to the sixth are 14, 51, 153, 325, 810, 1,871—in total, including variables and nebulae, 3,256. The regular increase shows the incompleteness of the former work for the faint stars. In the catalogue added to the maps the brightest and faintest stars of each class were specially indicated, as with Ptolemy; he designated the sub-classes, e.g. of the third magnitude, by 3; 2,3 and 3,4.

His example was followed by Eduard Heis at Munster, who, because

of his sharp eyesight, was able to distinguish fainter stars, which he indicated by 6,7. His *Atlas coelestis novus*, appearing in 1872, contained 5,421 stars, far more than Argelander's. Since both astronomers lived in Germany, the southern part of the sky below 40° of southern declination was omitted from their work. This hiatus was filled when the American astronomer Benjamin A. Gould (1824–96), expelled from the observatory at Albany through a quarrel with the 'Board of visitors', was called to Cordoba in the Argentine to organize an observatory. The extreme clarity of the sky allowed him and his assistants to add a seventh magnitude in the *Uranometria Argentina*, atlas and catalogue, which appeared in 1879. By careful intercomparisons of the stars, the precision could be increased and their brightness, by adding one decimal, expressed in tenths of a magnitude.

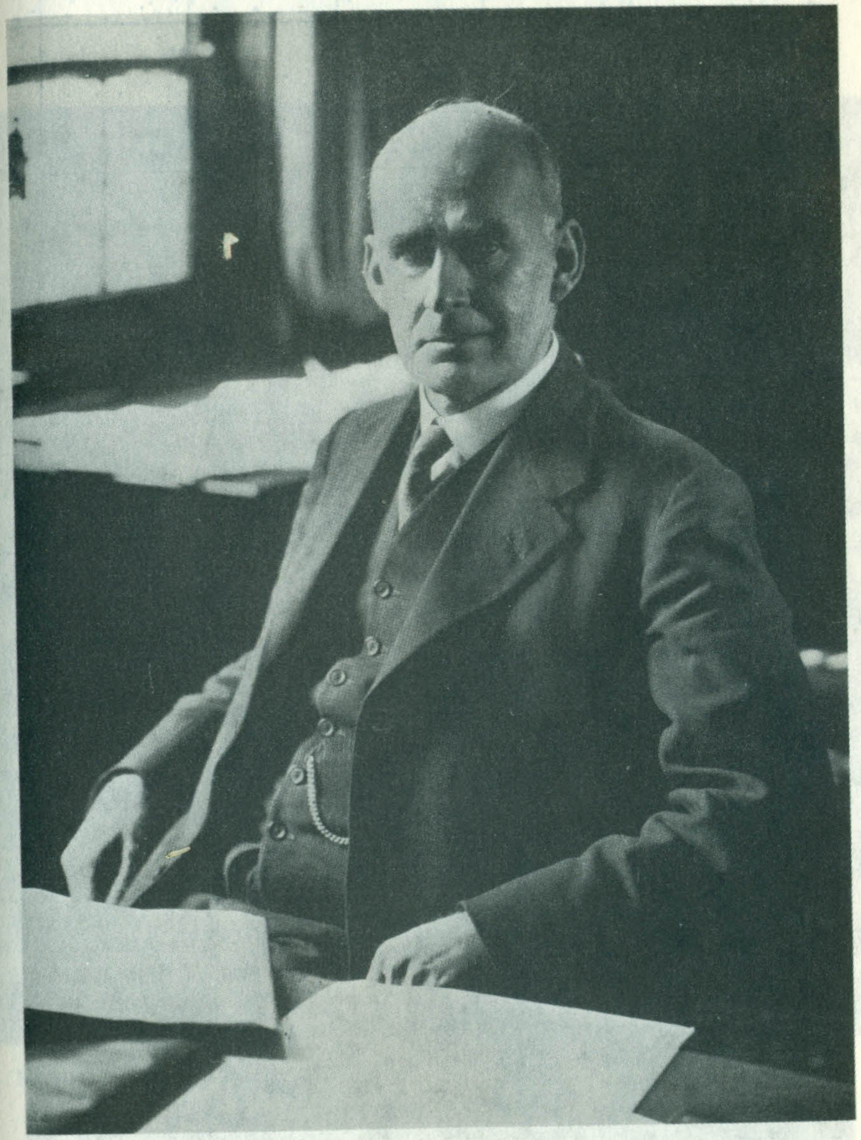
This greater precision was not entirely new. The steps used by Argelander for variable stars corresponded to nearly 0.1 magnitude. The signs (commas, dashes and points) used by William Herschel in his sequences of stars also denoted small fractions of a magnitude; but his observations, though published, were left unreduced. John Herschel, continuing his father's work during his stay at the Cape of Good Hope (1834–37), arranged sequences of bright southern stars and in this way could express their magnitudes with two decimals added.

It must be remarked that the addition of decimals fundamentally changed the character of 'magnitude'. From a quality, a class, an ordinal number, a basis of statistics, it has turned into a quantity, a measure, an amount that can be divided into fractions, a basis of computation. We cannot very well speak of a star of the 2.78th magnitude; but we can say that its magnitude is 2.78.

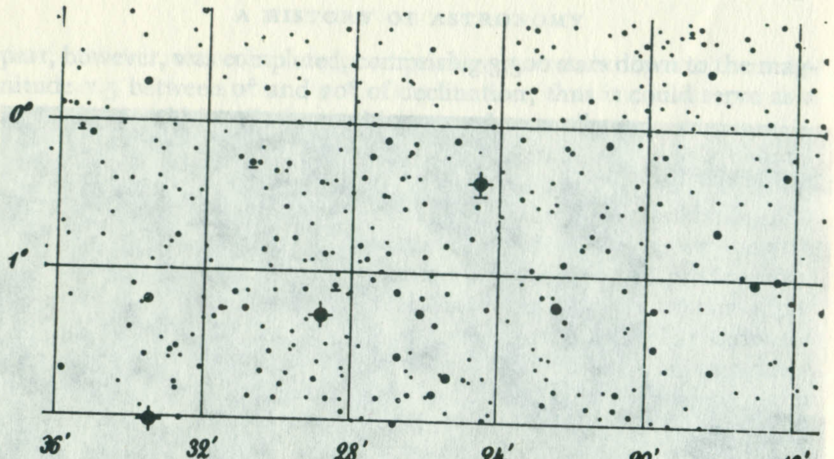
What difference in brightness is expressed by 1 magnitude? The opinion of William Herschel—also accepted by his son—was mentioned in Chapter 31; they supposed that a star of the first magnitude, if removed to twice or three times or seven times its distance, would appear as a star of magnitude 2, 3 or 7; this means that their brightness can be represented by $\frac{1}{4}$, $\frac{1}{9}$, $\frac{1}{49}$. At the same time, he estimated that the light radiated by a first-magnitude star was 100 times that of a sixth-magnitude star. In 1835 Steinheil expressed his opinion that magnitudes of stars do not indicate differences but ratios of light intensity; he derived the ratio for 1 magnitude to be 2.83. This was in accordance with what later on, in 1869, was formulated exactly by Th. Fechner as the 'psychophysical law': what the eye experiences as an equal difference in brightness is not a constant difference but a constant percentage of the quantity of light. He was led to this conclusion by the observation that in a cloud the differences between white and grey parts remain equally part, however, was completed, comprising 3,500 stars down to the magnitude 7.5 between 0° and 20° of declination; thus it could serve as a model but could hardly be used in general researches.

What we measure in this way, the brightness of a star, is a characteristic for us, but not for the star itself; it is apparent brightness. It determines the aspect of the starry heavens, which, as mankind's great experience of nature, unchanged through all centuries, we have in common with our barbarian ancestors and our classic predecessors. Every modern astronomer, however, has been aware that stars apparently connected into one time-honoured constellation, like Orion or Cassiopeia, do not really belong together but could be at widely different distances, one behind the other. This was so self-evident that it caused a certain shock when Proctor in 1869 and, more definitely, Klinkerfues at Göttingen in 1878 concluded from the proper motions that, among the seven chief stars of the Great Bear which form the Wain, the five in the midst belong together and, like a shoal of fishes or a procession of wagons over a field, run after one another in the direction of the Eagle. A second surprise was Hertzsprung's discovery, in 1909, that Sirius keeps pace with that procession like a fellow-traveller. More such processions have been discovered.

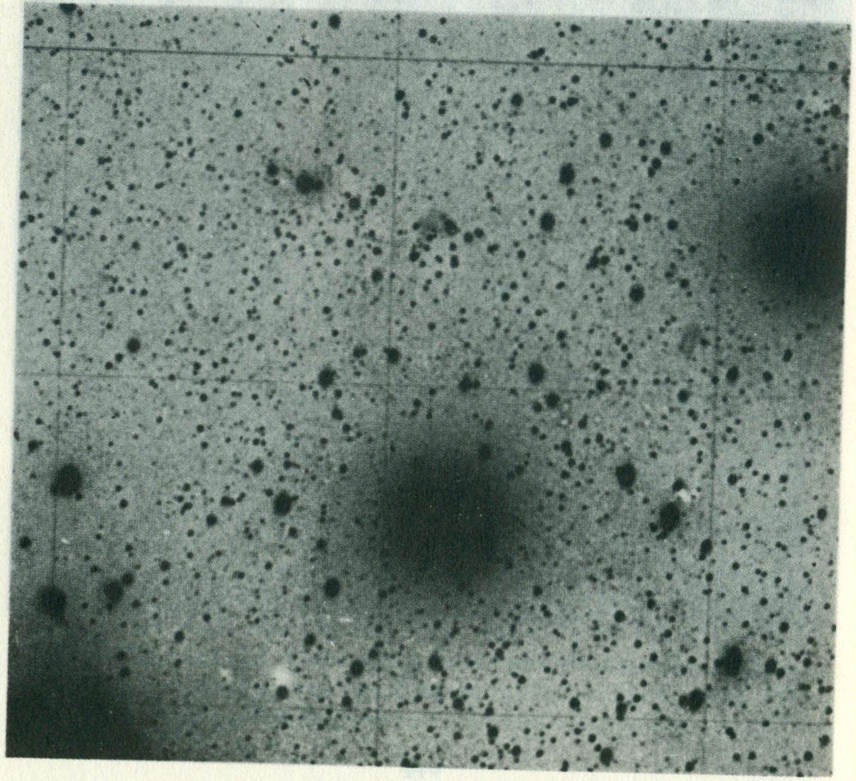
The apparent magnitudes, which make the brightest stars appear to us like one family, depend greatly on the distances; from the parallaxes it was soon deduced that, for example, Sirius, Vega, and α Centauri owed their brightness to their vicinity; Canopus, Rigel, and Betelgeuse to their enormous real light power or luminosity that makes them a special class of stars. As soon as the astronomers had the photometric magnitude as well as the parallax of a star at their disposal, they could compute its luminosity. It was expressed by the 'absolute magnitude'—the magnitude a star would have if placed at a fixed standard distance. Though Kapteyn and others made the logical attempt to introduce 1 parsec for this standard distance, practical use led to the adoption of 10 parsecs, with a standard parallax of 0.1″. Then the absolute magnitude (M) is found from the apparent magnitude (m) by adding 5 times the logarithm of 10 times the parallax. Thus for Sirius ($m=-1.4$, $p=0.37''$), M was found to be 1.4; for α Centauri ($m=0.1$, $p=0.76''$), $M=4.5$; for Rigel ($m=0.3$, p at most $=0.01''$), $M=-4.7$ (or brighter), which is 6 magnitudes brighter than Sirius. On the other hand, taking faint nearby stars, we find for Bessel's star, the binary 61 Cygni ($m=5.6$ and 6.3, $p=0.30''$), $M=8.0$ and 8.7; and for the runaway 'Barnard's star' ($m=9.7$, $p=0.54''$), $M=13.3$, again 100 times fainter. The extreme values of absolute magnitude were found to differ by 18 or 20, corresponding to a ratio of 16 or 100 million in light power. When the sun was added, with an absolute magnitude of 4.8, it appeared that

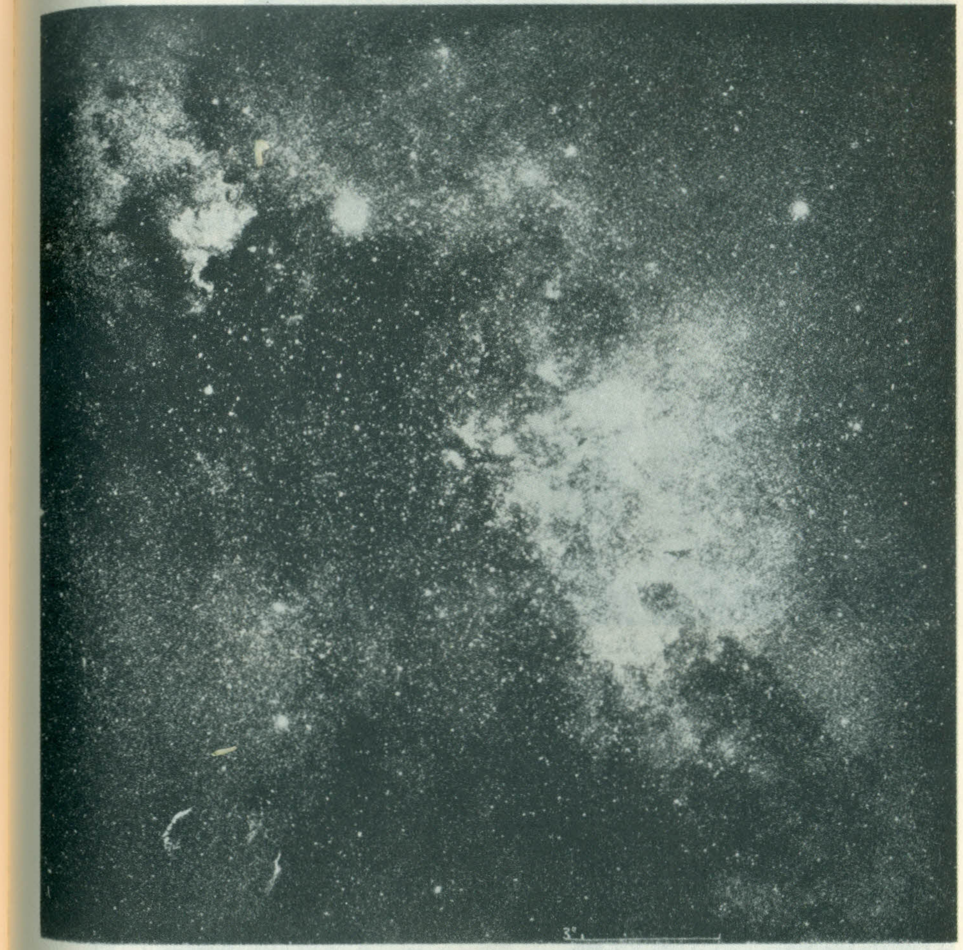


19. Sir Arthur Eddington (p. 417)

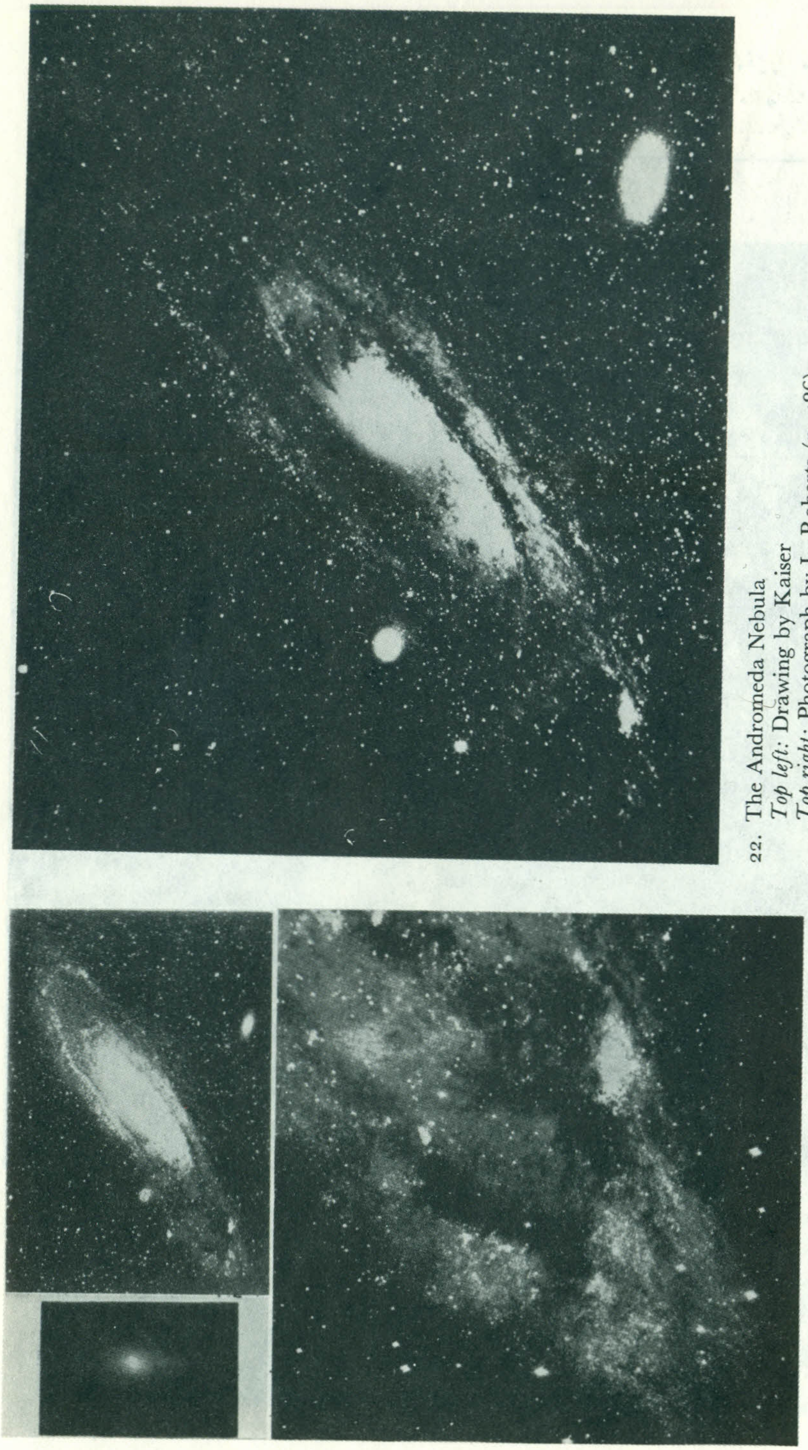


20. Telescopic stars in the Belt of Orion
Above: According to Argelander's atlas (p. 444)
Below: According to the Franklin Adams maps (p. 469)





21. Milky Way; Cygnus (p. 475)



22. The Andromeda Nebula

Top left: Drawing by Kaiser

Top right: Photograph by L. Roberts (p. 486)

Bottom left: Photograph of the south-western outer edge. Mt. Wilson

Right: The Andromeda Nebula photographed in 1901 by Ritchey and Pease

it is in the middle between stars 10,000 times brighter and 10,000 times fainter. Jeans denoted them by the descriptive names of 'lighthouse' stars and 'glow-worm' stars.

Whereas differences in the light power of the stars cannot be seen but only computed, differences in colour can be observed directly and have been known since Ptolemy. Struve was struck by the strongly—partly subjective—contrasting colours in double stars, which he described as red and blue or green. Zöllner constructed his photometer to serve simultaneously as a colorimeter, by inserting a plate of quartz into the polarized light pencil of the artificial star. The colours produced by rotating the quartz plate, however, were entirely different from the real stellar colours; the latter form a one-dimensional series from red through orange and yellow to white and bluish white; green shades, appearing by contrast, do not really occur among them. They are the colours appearing in an incandescent body heated to increasing temperatures; the colour differences in stars have always been considered as indicating temperature differences. When reddening occurs through absorbing nebulae or atmospheres, the colours remain within the same series.

This was clearly recognized by Julius F. J. Schmidt, who observed the stellar colours and expressed them—as also had Herman J. Klein—by one number, estimated on a scale on which 0 designated white, 4 yellow, and 6 to 10 shades of red of increasing depth (or saturation). His colour estimates, however, comprise only a moderate number of bright stars; the interest in star colours at the time was not very great. When making their photometric measurements, the Potsdam observers also estimated the colours; they expressed them not by a number but by letters indicating the names white, yellow (*gelb*), red: W, GW, WG, G, RG, GR, R, the scale being refined by adding + or −. Such letters indicating yellow, orange, and red hues (W, Y, OY, O, OR, R) were also used in 1884 by Franks, who did not restrict his colour estimates to a one-dimensional series but, by adding numbers for the degree of saturation, used a two-dimensional scheme. A most important contribution to the knowledge of stellar colours was given by H. Osthoff, an amateur in Cologne, who in the years 1883–99 estimated the colour on Schmidt's scale for a thousand stars. By careful practice he attained such accuracy that his results have a mean error of only 0.2 units. An equally extensive work in colour estimates of mainly reddish stars was performed by Fr. Krüger. Later on, K. Graff constructed a colorimeter in which a wedge of red glass gives to an artificial star all colours from white to red; the equality of colour must of course be estimated by eyesight.

Progress in science usually consists of replacing estimates of quality by measurements of quantity. Thus, instead of colour estimates, came the determination of 'colour equivalents', which are quantities directly connected with colour. When the photographic magnitudes of the stars could be measured accurately, the difference between visual and photographic magnitude, from 0 for white stars to 2 magnitudes and more for red stars, could be used as a 'colour index'. Another colour equivalent, introduced by G. Comstock, was the 'effective wavelength', the weighted mean of the wavelengths active in producing the photographic image. Comstock determined it by putting a coarse grating before the objective and afterwards measuring the distance from the short sideways spectra to the central stellar image; thus for white and for red stars he found 4,100 and 4,400 Å. All these different colour indications are expressions of the same basic fact: the distribution of intensity over the spectrum, which, according to Planck's formula, with increasing temperature shows an increasing preponderance of the shorter wavelengths.

The spectra themselves, however, fully disclose the diversity in the nature of stars. Our real knowledge of the nature of the stars begins with the discovery of spectrum analysis. Our science of these brilliant bodies that fill the universe with their radiation has been created by nearly a century of study of the stellar spectra.

Fraunhofer in 1817 perceived, and in 1823 described in detail, the fact that in the spectrum of Castor and Sirius dark lines presented themselves clearly different from those in the solar spectrum. He was, however, much too busy with his optical work to give more attention to this fact, and he died too soon to come back to it. After Kirchhoff had laid the basis of spectrum analysis and shown the meaning of the dark lines, spectroscopes were attached to telescopes to produce sufficiently bright stellar spectra for study. Besides Rutherford in America and Donati in Italy, there were William Huggins in his private observatory at Tulse Hill in England, and Father Angelo Secchi at the Specola Vaticana at Rome, who most thoroughly cultivated the new field. Huggins studied the spectra of a number of bright stars, identified the dark lines of sodium, iron, calcium and magnesium, and stated in 1863 that the same elements are present in the stars as in the sun and on the earth. Thus the unity of the material constitution of the entire universe, previously only assumed, was demonstrated with certainty.

Secchi, during 1863–68, examined the spectra of over 4,000 stars and found that they could be classified into four types, with some very few intermediate or deviating forms (plate 17). The first type, comprising more than half the number of visible stars, all white or bluish, showed four strong absorption lines, one in the red, one in the green, two in the blue-violet, all due to hydrogen, and moreover some very faint other lines. The second type, consisting of yellow stars (Capella, Arcturus, Aldebaran), showed a spectrum resembling that of the sun: numerous

narrow lines identical with the solar lines but somewhat stronger in the last-named stars. The third type, the red stars (Betelgeuse, Antares, α Herculis, Mira), moreover, showed dark bands sharply cut at the violet side and gradually fading towards the red.* His attentiveness in this observation is shown by his discovery (in 1868) of a fourth type, faint and fiery-red stars, showing different bands fading towards the violet side and corresponding in wavelength to the emission bands of electric discharges in hydrocarbons. He also perceived some few exceptional stars, such as γ Cassiopeiae and the variable star β Lyrae, which showed bright emission lines, as also did the nova appearing in 1866 in Corona.

Huggins in 1864 directed his spectroscope to the planetary nebula in Draco and discovered that the spectrum consisted of only one bright and two fainter green emission lines; one of the latter was the green line of hydrogen (Hβ), and the other two were thought to be due to nitrogen. The same was the case with the great Orion Nebula. Thus was answered the question posed by William Herschel: whether there are nebulae that do not consist of a number of stars but of a 'shining fluidum'. There are; the spectrum shows them to be a thin, glowing or luminous gas. The cause of the luminosity could not be exactly indicated; electrical discharges in a tube with rarefied gas could serve as an instance of what was indicated by the term 'luminescence'. Such gaseous nebulae are few in number; most non-resolvable nebulae, among them the large Andromeda Nebula, showed a continuous spectrum, so that they must be clusters of densely-packed small stars.

Huggins also was the first to determine, according to Doppler's principle, the radial velocity of a star through the displacement of its spectral lines (cf. figure in plate 15); his example was soon followed at Greenwich Observatory. The measurements, however, were so difficult that the results were often uncertain by tens of kilometres. An essential improvement was made when, in 1887, Vogel and Scheiner at the Potsdam Observatory constructed a spectrograph with proper provisions against a flexure and changes of temperature. Now the results had such greater accuracy that the orbital velocity of the earth was clearly shown by a periodic change in the measured radial velocity of the stars. Thus the validity of Doppler's principle—previously doubted by some physicists—was demonstrated, as well as the yearly motion of the earth, for whomever might need it.

Secchi's four types of spectrum have remained in use as a main classification. Vogel called them classes I, II, III*a* and III*b* and considered them as phases in a natural development; through cooling, class I

*** In his publications Secchi adorned his pictures of the spectra with their real colours which we have left out of our reproduction.**

stars change into class II and class II into class III*a* or III*b*. Subdivision I*b* for white stars with narrow lines, as well as I*c* and II*b* for stars with bright lines, disturbed the regularity; moreover, the question was raised as to whether it was safe to identify a formal classification with an evolutionary theory. A classification of all the stars brighter than the seventh magnitude was started on these lines at Potsdam. When, however, the zone between 0° and 20° of declination had been finished, the work was not continued; for in the meantime photography of stellar spectra had advanced and replaced the laborious peering at faint colour bands by an easier and more reliable working method.

Here Henry Draper of Virginia and Huggins in England were the pioneers. Draper had ground a mirror of 72 cm., and, by placing a quartz prism (quartz does not, as does glass, absorb the ultraviolet rays) before the focus, he succeeded in 1872 for the first time in photographing a stellar spectrum (of Vega). In 1879–82, working with a 28 cm. refractor and a Browning spectrograph, he photographed the spectra of fifty stars. Soon after Draper, Huggins succeeded in photographing stellar spectra (pl. 17). His attention was drawn to the remarkable regular series of absorption lines in the spectrum of Vega, Sirius and other white stars; since they joined and continued the hydrogen lines in the blue and violet at decreasing mutual distances, he did not hesitate to ascribe them to hydrogen. They were the same lines that had been photographed shortly before in the chromospheric spectrum and that shortly afterwards could be represented by Balmer's formula.

After Draper's death in 1882, his widow bequeathed all his instruments and a sum of money as a 'Henry Draper Memorial Fund' to the Harvard Observatory to continue his work on stellar spectra. Seldom has a moderate amount of money been so well spent for science. Pickering used it to provide the objective of a wide-angle telescope with an objective prism, a large glass disc ground into a prism with small refractive angle. Thus the images in the focal plane became small spectra, instead of round star points; one plate contained the spectra of all the hundreds of stars of a large field at the same time. They were classified according to their aspect and were indicated by letters A, B, F, G, K, M, N—representing really different classes of spectra. A and B corresponded to Secchi's first type; F, G, K, to the second type; M was identical with the third and N with the fourth type. The first *Henry Draper Catalogue* in 1890 gave the spectra of 10,000 stars, among which, in the case of faint spectra and hardly visible lines, many erroneous allocations still occurred and had to be corrected afterwards. The work was then continued with larger instruments; the 10 inch Bache telescope was provided with two objective prisms of some few degrees refracting angle, which used separately served for faint stars and

combined for bright stars. By taking the same kind of plates at Arequipa, the work was extended over the entire southern sky.

The spectra of the bright stars taken with the larger dispersion were investigated by Antonia C. Maury. She distributed them over 24 classes, designated I–XXIV; this more detailed distinction, however, did not meet with general acceptance. In a number of bright stars in Orion, whose spectra were classified in classes I–IV, corresponding to the B stars of the *Draper Catalogue*, she perceived a number of characteristic lines, which for the moment were called 'Orion lines'; they had also been found by Vogel and Scheiner in some of their stars. After terrestrial helium had been discovered by Ramsay in 1895, it appeared that all these 'Orion' lines were helium lines. In each of the classes, moreover, she distinguished stars with broad, with very broad, and with narrow lines by adding the letters 'a', 'b', 'c' to the Roman numbers. The lines in the sub-class 'c' were not only narrower than in 'a' but also different in relative intensity; she added a list of lines that are strong in the 'c' stars and pointed out that these lines probably constituted a separate characteristic group. The importance of the 'c' stars was shown afterwards.

Pickering's chief aim with all these plates was to extend the survey of stellar spectra down to the ninth magnitude, a 'mass production'. Such a work never could have been accomplished by means of slit spectra of all the separate stars. Slit spectra, because they are not blurred by air vibrations, are necessary for refined study of the spectral lines, whereas the spectra taken with the objective prism, less sharp through unsteady air, are used for classification. The classification in this case was the work of Annie J. Cannon, who acquired a special ability in distinguishing minute gradations. She used the system of letters of the first *Draper Catalogue*, which in this way, in spite of its queer origin, became dominant in the field of stellar spectra (pl. 18). It appeared that the different classes indicated by these letters formed a continuous series with gradual transitions: from the B stars (with helium lines) and A stars (with broad hydrogen lines), through F, G (the exact solar type), and K, to the M stars (with bands). The transition forms were indicated by numbers forming a kind of decimals: B0, B5, B8; A0, A2, A5, A8; F0, etc.; the estimates could not very well be made more precise than ¼ of a class; exact decimals appeared in later times as the result of measurements. All but one single per cent of the totality of stars could be classed in this series, especially after side branches of R–N stars (with different band systems) were added at the end and O stars at the beginning. Thus, after many years of work, the great *Henry Draper Catalogue*, giving magnitude and spectrum of 225,000 stars, was completed and published in 1918–24 in nine volumes of the Harvard Annals.

The above-named letter O was introduced for some rare peculiar spectra, showing bright, mostly broad, emission lines on a continuous background; the strongest had wavelengths 4686 and 4650. The first stars of this type—fifth and sixth-magnitude stars in a bright galactic patch in the Swan—had already been discovered visually in 1867 by the Paris astronomers C. Wolf and G. Rayet; hence this kind of stars was often designated as 'Wolf-Rayet stars'. On the plates of the southern sky Pickering detected a second-magnitude star in the Ship, γ Velorum, as the brightest of this type, sometimes called the 'fifth type'. Still more important was the discovery, in 1896, of the peculiar spectrum of another bright star in the Ship, ζ Puppis. Between the hydrogen lines it showed other lines of nearly the same intensity, alternating with them so regularly that Pickering could represent their wavelength by Balmer's formula when, instead of the whole numbers 3, 4, 5 . . , the values 3½, 4½, and 5½ were inserted. So this 'Pickering series' was ascribed to hydrogen in some unknown abnormal condition. Rydberg pointed out that then the line with wavelength 4686, exactly $\frac{5}{7}$ times that of the first Balmer line Hα, also belonged to this spectrum. Since it is the brightest line in the O stars and since, morover, the lines of the Pickering series here are faintly visible, a bridge was built to the Bo stars, where they occur as faint absorption lines. Thus the O stars found their place preceding the B stars.

The series of spectral classes indicated by these letters, from O and B to M and N, was a series of decreasing temperature. The idea that it was a series of consecutive stages of development, due to cooling, as formerly expressed by Vogel, was a self-evident conclusion. However, there were difficulties. Cooling means decrease in intensity; and small bodies cool more rapidly than large ones. Monck, in 1892, pointed out that the frequent occurrence of double stars consisting of a bright red and a faint blue-white component contradicted this scheme of evolution.

An entirely different theory had formerly been proposed by Lockyer. Lockyer not only enriched astrophysics with many practical instruments and new discoveries but also became renowned through original, sometimes fantastic, new theoretical ideas, laid down most extensively in his *Chemistry of the Sun* (in 1887) and *Inorganic Evolution* (in 1900). Through his observations of spectra in the sun and in the laboratory he had gained the conviction, first expressed in 1878, that the atoms of our chemical elements were not really elementary particles but that, under high temperature or strong electrical discharge, they broke up into simpler constituents, which he called 'proto-elements'. They were characterized by special spectral lines, which were enhanced when going from the arc spectrum of an element to the high-tension spark spectrum; he called them 'enhanced lines', and they are often denoted

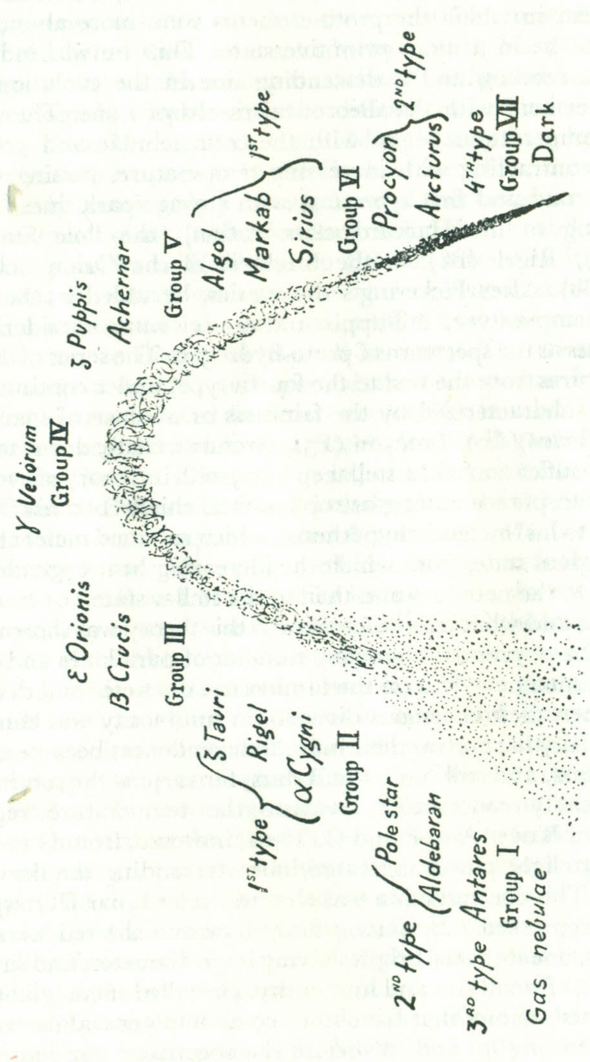


Fig. 34. The evolution sequence of the stars according to Lockyer. (Names of typical stars are added, as found in his theory of 1900)

as 'spark lines'. They were, as he remarked in 1900, the same lines that Miss Maury had found to be strong in her 'c' stars. In his many photographs of stellar spectra Lockyer found that among stars of the same spectral class some had very strong enhanced lines, others had them faint; the first, in which the proto-elements were more abundant, he considered to be in a more primitive state. Thus he was induced to assume an ascending and a descending line in the evolution of the stars, in agreement with the theoretical results of Lane. The series of ascending temperatures began with the cold nebulae and proceeded along stars contracting with increasing temperature, passing through the third, second and first type stars with strong spark lines: Antares (M according to the Harvard classification), the Pole Star (F8), Deneb (A2), Rigel (B8) to the brightest of the Orion belt stars: ε Orionis (B0). After Pickering's discoveries, he added, as the highest summit of temperature, ζ Puppis and γ Velorum, considering the Pickering lines as the spectrum of proto-hydrogen. The series of descending temperatures from the first to the fourth type, under continued contraction, was characterized by the faintness or absence of spark lines: Algol (B8), Sirius (A0), Procyon (F5), Arcturus (K0), down to the N stars. This classification of the stellar spectra, with its theory of evolution, found little acceptance among astrophysicists, chiefly because Lockyer had linked it to his 'meteoric hypothesis', which assumed meteor swarms to be the original state, from which the increasing heat engendered by collisions led to the nebulous and then to the stellar state.

What value and what truth there was in this theory was shown when, in the next dozen years, the growing number of parallaxes and proper motions presented new data on the luminosity, diameter and density of the stars. When their enormous diversity in luminosity was connected with the diversity in spectra, their mutual dependences became clearer. That the A stars, and still more the B stars, far surpass the sun in luminosity was easily conceivable, because the temperature regularly decreased from B over A to F and G. Then, however, from G to K and M the average light power increased, notwithstanding the decreasing temperature. This contradiction was cleared up by Ejnar Hertzsprung, who in 1905 remarked that among the yellow and the red stars there were two sorts, one sort very bright, having large diameters and surfaces; the other faint, of small size and luminosity. He called them 'giant stars' and 'dwarf stars', names that have since come into general use and are indicated by adding 'g' and 'd' before the spectrum; our sun is dG0 (0 = zero). The ruddy K and M dwarfs, numerous in space but faint, are visible only when situated in the nearest surroundings of our sun, so that they form a small minority, recognizable by large motion and parallax among the bulk of the remote giants, which, though outnumbered by the dwarfs in a volume of space, are visible over a thousand times larger spaces and thus determine the average large luminosity.

At the same time Hertzsprung found that Miss Maury's 'c' stars were distinguished by imperceptible parallaxes and small, nearly imperceptible, proper motions, so that they must be situated at a great distance and hence must have a high luminosity; 'they may perhaps correspond to the whales among the fishes'[212] as he said in a zoological metaphor, rightly emphasizing the differences in kind; 'supergiants' they have since been called. Since Miss Maury had found the 'c' characteristics to be present in the Cepheid variables, these, too, must be, as already mentioned, gaseous spheres of enormous size.

The treatment of all the data on luminosity, density and spectrum by Hertzsprung and by H. N. Russell in Princeton resulted in the famous Hertzsprung-Russell diagram, a graphic representation of the relation between spectrum and absolute magnitude, best known in the often reproduced figure drawn by Russell in 1913. The co-ordinates are absolute magnitude (M) and spectral class; every star is given by a point, and values deduced from an average of a number of very small parallaxes are represented as open circles. In this diagram it is seen that the stars are situated along two belts, one horizontal at $M=0$, with giant stars in all classes a hundred times brighter than the sun; the other inclined, following a sequence from A stars with $M=0$ decreasing to $M=3$ for the F stars, $M=5$ for the G stars(the sun among them), to $M=7$ and 10 for K and M stars. The inclined belt, since it contains the greater majority of stars, was later on mostly called the 'main sequence'. Red dwarfs of the M type, of extremely small luminosity ($M=10-15$), continue the main sequence at its lower end. White giants of the B and O type ($M=-1$ to -5) continue it at its upper end. Sparse supergiants of all types are situated above the belt of common giants.

The wide gap between the two kinds of yellow stars could be demonstrated by Russell in a striking instance. Among the numerous eclipsing variables, almost all of the B and A types, two were found of the G type —W Ursae, with a period of 8 hours and W Crucis, with a period of 198 days. The densities, computed as explained above (Chapter 39) were found, for the former, to be twice, for the latter, $\frac{1}{600000}$ the sun's density. The former is a common dwarf, the latter must be an enormous ball of thin gas, i.e. a supergiant.

A queer object, not fitting in with either of the two sequences and represented by a lonely point at the lower left-hand side of the diagram, was found in a small star of the tenth magnitude in Eridanus. With a smaller adjacent star, it forms the binary o_2 Eridani, with a period of 200 years. It has a large proper motion and a large parallax of 0.20″; hence it is a dwarf with a luminosity 400 times smaller than the sun.

From its orbital motion a mass of 0.4 times the sun's mass was derived; mass and luminosity correspond to the red dwarfs of the M type. It was found, however, to be a white star of spectral class A, the first specimen of a 'white dwarf'. The companion of Sirius is also a faint star with a moderate mass, to which special attention has already been given. In 1915 W. S. Adams at Mount Wilson succeeded in photographing its spectrum, notwithstanding the glare of Sirius' light in which it is drowned; it contained nothing but broad hydrogen lines; hence it must be an A type (or, at most an F star). It was a second white dwarf, occupying a special place in the diagram beside the Eridanus star. This isolation from all the other stars symbolized their entirely mysterious character—small luminosity, moderate mass and strong radiative power. Either it must have a very small size with an enormous density of 60,000, or it must be a large dark sphere with a small piece of surface, radiating white-hot—both equally absurd.

Russell in 1913 immediately identified his diagram with Lane's theory of evolution. The branch of ascending temperatures was represented by the horizontal belt of giant stars; because the decreasing size here was compensated for by increasing temperature, the luminosity remained constant when the star developed from a red to a white giant. On the descending branch temperature and size both decreased and the star rapidly declined in luminosity along the inclined belt of the main sequence. He pointed out that Lockyer was thus justified in respect of the main question of an ascending and descending branch; but his allocation of the third type to the former and the fourth type to the latter had been too rough. Now the spectral differences also fitted into the picture; Lockyer's enhanced lines characterizing the ascending branch were identical with Miss Maury's 'c' lines characterizing the biggest supergiants.

The correlation between the luminosity of the star and the intensity of special lines in the spectrum, so clearly exhibited by the 'c' stars, appears also, though in a lesser degree, when we compare common giants with dwarfs. When these qualitative differences could be brought into the form of a quantitative relation, it would become possible to derive the luminosity of a star from the intensity of its spectral lines. Kohlschütter and Adams at the Mount Wilson Observatory developed this method in 1914–18 by taking spectra of nearly all the accessible F, G and K stars. For every spectral class or subclass, all the available data of parallax and proper motion, transformed into absolute magnitudes, were used to derive empirical tables of mutual dependence; they served to derive the absolute magnitude for all the other stars. Comparison of this absolute magnitude with the apparent magnitude at once gave the parallax of the star. Thus, in an unexpected way, parallaxes

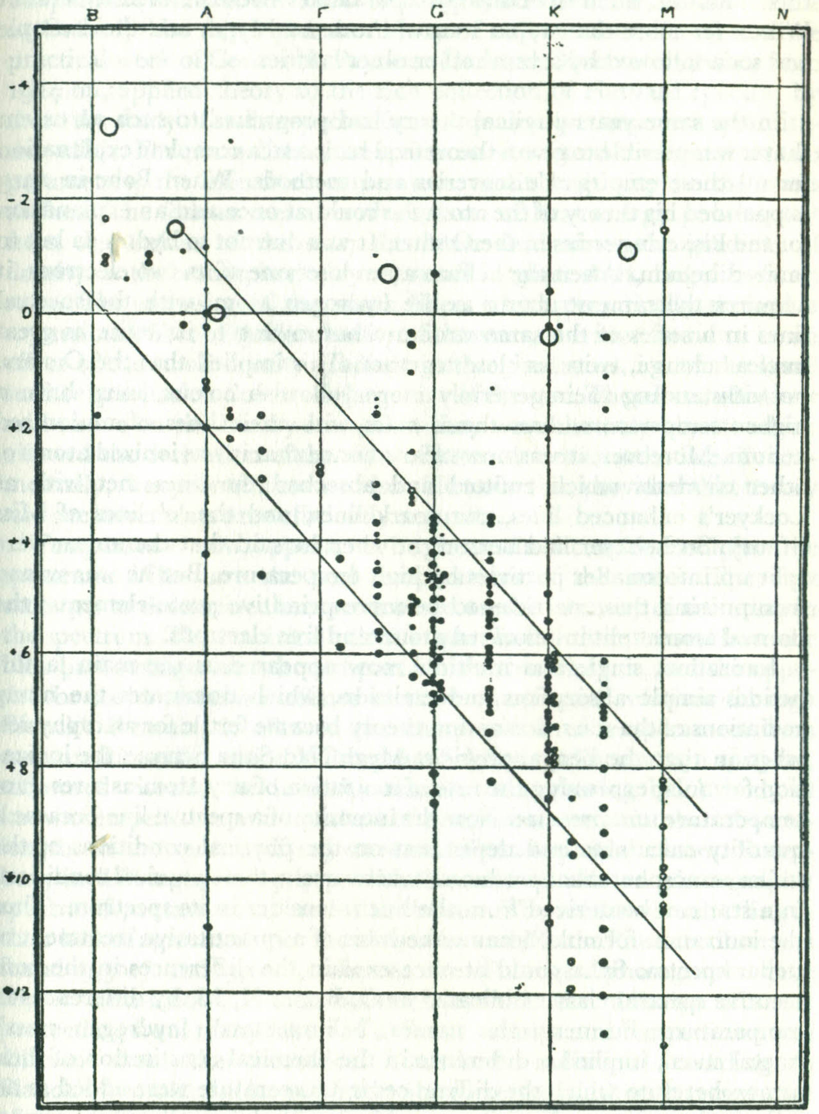


Fig. 35. Russell's diagram

far too small to be measured directly could be found and used in studies on the structure of the stellar system; they were reliable to about ⅕ of their amount. Such 'spectroscopic parallaxes' were derived at Mount Wilson for more than 1,400 stars of the second type, and the example was soon followed by several other observatories.

In the same years physical theory had progressed to such an extent that it was possible to give a theoretical basis and a complete explanation for all these empirical discoveries and methods. When Bohr in 1913 expounded his theory of the atom, he could at once add an explanation for the Pickering series in the O stars. It was due not to hydrogen but to ionized helium. When the helium atom loses one of its two electrons, it acquires the same structure as the hydrogen atom, with the spectral lines in a series of the same structure but, owing to its twice as great nuclear charge, twice as close together. This implied that the O stars, notwithstanding their generally more yellowish colour, must have a higher temperature than the B stars with their lines of un-ionized helium. Moreover, it was now clear at once that it was ionized atoms of other elements which emitted and absorbed the lines met with as Lockyer's enhanced lines, our spark lines, and the 'c' lines of Miss Maury. So Lockyer had been right when he said that the atoms were split up into smaller particles by high temperature. But he was wrong in supposing these particles to be more primitive proto-elements; the normal atoms split into ionized atoms and free electrons.

Ionization, single and multiple, now appeared as the main factor, besides simple absorption and emission, which dominates the many radiations of the stars. Ionization theory became fertile for astrophysics, when in 1920 the Bengal physicist Megh Nad Saha derived the ionization formula, expressing the rate of ionization of any atom as a result of temperature and pressure. Now the intensity of a spectral line became a quantity calculable and dependent on the physical conditions of the stellar atmosphere that produced it; conversely, these physical conditions in a star can be derived from the line intensities in its spectrum. Thus the ionization formula became the basis of a quantitative treatment of stellar spectra. Saha could at once explain the differences in the consecutive spectral classes indicated as O, B, . . . K, M, by differences in temperature. Formerly the names 'helium stars', 'hydrogen stars', 'metal stars', implied a difference in the chemical constitution of their atmospheres, to which the differences in temperature were added as an independent datum. Now it was evident that chemically equal atmospheres, if increasing in temperature, had to show the sequence of M, K, G, F, A ,B, O spectra. Moreover, Saha's formula, indicating the increase in ionization by decrease in pressure, explained the great

intensity of the enhanced lines in the voluminous giant stars with their small density. By the theoretical work of H. N. Russell at Princeton, who adapted the ionization formula to astrophysical practice; of E. A. Milne at Oxford, who developed the theory of stellar atmospheres; and the practical work of Cecilia H. Payne at Harvard Observatory, who, from 1924 on, applied theory to the rich collection of Harvard spectra; by these the study of stellar spectra from a qualitative became a quantitative affair. For normal stars the spectrum was found to depend on two parameters, the effective temperature and the gravity at the star's surface. The former measures the stream of heat energy pouring out from the surface of the star; the latter determines the gradient of density in the atmospheric layers, small in giant stars, large in dwarf stars. The intensity of the spark lines, which empirically seemed a mysterious effect of the luminosity of the stars, was now found to be an effect of the small density gradient in the giant stars, i.e. of the small surface gravitation due to the large size of the star. Therefore, what was said above on the binary stars, that they were the only objects which allowed the derivation of the mass of a star, is not exactly true. Fundamentally, the spectral lines are also able to do this, provided that theory and measurements are sufficiently accurate.

Temperature now appears to be the main factor determining the spectrum. What are the real temperatures of the stars? The first attempts to determine them were based on the intensity distribution in the spectrum. The empirical rule that stars hotter than the sun have the blue part stronger and the red part fainter than the sun, and the opposite for cooler stars, was refined to exact quantitative relations through Planck's formula; it allowed the computation of temperatures from measured intensity ratios. Wilsing and Scheiner at Potsdam, in 1905–10, measured visually the intensity relative to a glowing black body of known temperature as a standard of comparison for a number of wavelengths in the spectra of 109 stars of different spectral classes. Rosenberg in Tübingen in 1914 published measurements on photographic spectra of 70 stars, compared with the sun. The results were startling in their lack of agreement; for the classes Ao and Mo the Potsdam observers found 9,300° and 3,100°, whereas the Tübingen photographs gave 28,000° and 2,600°. It soon became clear that the radiation of a star proceeding from many layers of different density and temperature was different from the theoretical black-body radiation according to Planck's formula. Each result had to be corrected, and, with some range of uncertainty, a value of 10,000°–11,000° for Ao and 3,000° for Mo could be adopted.

The helium stars of class B were hotter than the A stars; their temperature could not be found in this way, because space absorption, which is strong on account of their great distance, makes their colour more yellowish. Here the spectral lines came to the rescue. By observing the appearance and disappearance of the lines of once, doubly and trebly ionized silicon in the sequence of A, B and O stars, Cecilia Payne in 1924 could establish a scale of temperatures for these stars: for B5 to B0 they increased from 15,000° to 20,000°. The first O stars (O9 and O8) had 25,000°–30,000°–; farther on, the increasing strength of the lines of ionized helium, as well as the lines of equally difficult ionizable oxygen, nitrogen and carbon atoms (among them the strong Wolf-Rayet line 4650), indicated still higher temperatures, but she could not exactly determine them.

This was done by Zanstra in 1925 by an entirely different method. The radiation of a high-temperature star, of 30,000° or more, consists almost entirely of far-ultraviolet wavelengths invisible to the eye and not accessible even to photography, because all wavelengths below 3,000 Å are absorbed by an ozone layer high in our atmosphere. According to Planck's formula, the radiation of such a star is strongest at wavelengths of about 1,000 Å; the wavelengths above 3,000 and 4,000 Å, through which we photograph or see the star, constitute the small extreme border part of its radiation. The invisible wavelengths of great intensity below 911 Å consist of large quanta and exert a strong ionizing power upon the hydrogen atoms in surrounding space. In recombining to normal atoms these ionized hydrogen atoms emit the lines of hydrogen, among them the Balmer series; our plates and eyes are sensitive to these wavelengths, and we see this surrounding matter as a faint nebula (a planetary or a ring nebula), emitting hydrogen and other lines. Thus the gaseous nebulae are explained; Herschel's 'shining fluid' is an extremely rarefied gas of hydrogen and other atoms illuminated (in a complex way) by a high-temperature star. Wright at the Lick Observatory had established in 1918 that the central star visible in planetary or ring nebulae was an O star. The light seen around the star, produced by its strong invisible radiation, is far stronger than what we see directly as starlight. This difference was the basis of Zanstra's deductions; the higher the temperature of the star, the greater this difference between nebula and central star. Thus for nearly (or entirely) invisible stars in bright nebulae he could derive temperatures from 34,000° to 40,000°—in a single case up to 70,000°.

The matter did not rest here. In 1926 the Californian physicist Bowen had solved the riddle of 'nebulium', the fantastic element invented to explain the unknown lines in the spectrum of nebulae, among them the strong green line first discovered by Huggins, which did not occur in any terrestrial spectrum. They are so-called 'forbidden lines' of ionized oxygen and nitrogen, radiated in transitions so difficult and scarce that

in ordinary gases and atmospheres they are always forestalled by other transitions producing the common lines. Where the latter transitions are absent, in consequence of the extreme tenuity of matter and the faintness of radiation obtaining in the nebulae, the 'forbidden' transitions have a chance. Bowen pointed out that the smallest wavelengths in the stellar radiation consist of quanta so large that they are not entirely needed to ionize hydrogen and hence leave a large amount of energy to excite the oxygen and nitrogen atoms; these wavelengths are strongest in stars of the highest temperature. This means that the 'nebulium' lines relative to the hydrogen lines are stronger, the higher the temperature of the central star. Wright had already arranged the nebulae, according to the relative line intensities, as more or less excited; now it appeared that this was indeed a temperature sequence. Low in this sequence stand the bright extended nebulae in Orion and in the Ship, both excited by groups of O stars (in the former the quadruple star θ^2 Orion is called the 'trapeze'); they have a 'moderate' temperature of 30,000°. For the invisible stars of the most strongly excited nebulae, temperatures above 100,000° have been found.

Turning now to the other side of the scale of temperatures, we have 3,000° for a red M0 star like Betelgeuse. The characteristic bands discovered by Secchi and in 1907 found by A. Fowler to be produced by titanium oxide dominate the spectrum in cooler sub-divisions. For such low temperatures the maximum and main amount of radiation is infra-red invisible heat radiation; only a border of the smallest wavelengths is visible as red light. In the variable Mira stars the strong absorption bands do not permit the exact finding of the temperature by means of the gradient of spectral intensity. For the deep-red N stars, 2,000° is adopted; for Mira and analogous stars, Pettit and Nicholson at Mount Wilson, by radiometer measurements, derived temperatures at their maximum brightness of 2,400°–2,000°, which at minimum decrease to 1,300° or 1,400°. Though such stars radiate much infra-red heat energy, they are almost invisible. With plates sensitized to infra-red radiation, fairly bright stars have been photographed that are entirely invisible on ordinary panchromatic plates; their temperature must be below 1,000°, so that here we may suspect the transition to really dark stars. Whether they have a corresponding small mass we do not know.

Thus the range of surface temperatures of the stars extends from, say, 1,000° to 100,000°, where the extremes at both ends are almost, or entirely, invisible. This, of course, is due to the specialty of our organ of vision, that is especially adapted to the radiations of the sun. Red stars, which appear very bright to us, must also apparently be gigantic globes. Can we indicate how large they appear to us? We always speak of the stars as light points, indicating that they do not show as real discs; what it means can be readily computed. If a G star like Capella has the same surface temperature as the sun, its apparent brightness must be smaller in direct proportion to its apparent surface. Its brightness is 40,000 million times smaller than the sun's; hence its apparent diameter must be 200,000 times smaller than the sun's, i.e. 0.01″. This is indeed too small a disc to be recognized, because the diffraction disc (for a wavelength of 5,000 Å, i.e. $\frac{1}{2000}$ mm.) with a telescope of 40 inch or 1 metre aperture is 0.10″, ten times the real disc of the star. To reduce the diffraction disc to 0.01″, an aperture of 10 metres of 400 inches would be needed.

In 1890 it dawned upon the American physicist A. A. Michelson that such a small stellar disc could still be made perceptible. When the light of a star is caught by two mirrors at 10 metres distance and reflected into one telescope, the interference of the two light pencils produces upon the diffraction disc of the star a pattern of dark and bright lines, at a distance of 0.01″, corresponding to the distance of the pencils of 10 metres. This, however, holds for absolutely parallel light, i.e. a point-like star image. If the star is a very close double or has a real disc of 0.01″ diameter, the alternation of dark and bright lines would be smoothed out, and the line pattern would disappear. Though the basic idea was soon applied to the separation and measurement of close double stars, it was not realized until 1919, in the practical construction of an 'interferometer' at Mount Wilson. Anderson and Pease succeeded in determining the diameters of some few bright red stars: Betelgeuse, 0.045″; Antares, 0.040″; Arcturus, 0.022″; Mira, 0.056″. Only red stars were taken into account; white stars, in order to present such diameters, would have to appear hundreds of times brighter than they do. The measurements, though they constitute no new discovery, are important as a triumph of physical theory over technical limitations.

All that we can know of the stars through observation relates to their outer surface. What about their interior?

When dealing with the sun, we mentioned Eddington's researches on its interior. Here, however—so much wider was the scope of modern research—the sun was a chance object only, and the research dealt with the stars generally. Eddington's book, which in 1925 collected all his work in this field, had the title *The Internal Constitution of the Stars*, and his numerical data were taken from the best-known stars (plate 19).

The basis of Eddington's theory of the stars was formed by the concept of radiative equilibrium; with the high temperatures of millions of degrees obtaining here, radiation is the main and practically the only mechanism of heat transfer within the stars.

In the treatment of the conditions for thermal as well as for mechanical

equilibrium, three new points of view were introduced. First, the radiation pressure, theoretically deduced long before in Maxwell's theory of electricity; almost imperceptible in experiments on earth, it can carry in the stars an appreciable part of the weight of the matter, larger or smaller, depending on the intensity of the outward stream of heat. Secondly, the high degree of ionization; by these fierce radiations entire shells of electrons are torn from the atoms, down to the limit where the electrons are subject to be either torn away or caught up in recombination. In an endless play of ionization and recombination of the atoms and electrons and alternate absorption and emission of radiation, the energy is transported from the interior to the outside. Thirdly, the production of energy in the interior, which keeps up the outward stream of energy that the star is sending into space. These three kinds of phenomena determine the state of matter and energy in the stars: temperature, pressure, density, absorption coefficient, ionization of all kinds of atoms, as functions of the distance from the centre.

The most important result of Eddington's work was the mass-luminosity law, stating that the luminosity of a star—save for small, calculable deviations dependent on the spectral class—is entirely determined by its mass, according to a relation derived theoretically. In former years, in a study of the masses of binary stars, astronomers had perceived, with some surprise, that stars of the same mass but of different spectral class had almost the same luminosity. What had been found as a casual coincidence in a small assemblage of data Eddington showed to be a general law of fundamental importance. It gave a new outlook on the evolution of the stars and the meaning of the Hertzsprung-Russell diagram. If it is true that for constant mass the luminosity is also constant, then the inclined belt of the main sequence from the bright A stars to the faint M stars cannot be a line of evolution by cooling. The theory of evolution which the diagram was supposed to illustrate cannot be right and must be replaced by a new one. The stars, in keeping their mass, must follow a horizontal line in the diagram, from the right to the left when increasing in temperature and then back when getting cooler; the main-sequence belt represents the crowding at the reversal of the change. The smaller the mass, the lower is the line of evolution situated in the diagram and the lower the maximum temperature.

Eddington had derived the mass-luminosity law on the assumption that stellar matter, as might be assumed for the giant stars, behaved like a perfect gas. When in 1924 he compared his results with the practical data of a number of stars, chiefly to see what deviations would be shown by the dense dwarf stars, he found to his surprise that the latter entirely conformed to the law: they behaved as if they consisted of thin gas. He soon understood the cause; the atoms in the deep layers of the star, having lost their outer shells of electrons in their high degree of ionization, occupy so small a volume that, even with high density, they freely run their course unhampered by one another. An unexpected consequence followed immediately: these stripped atoms can be so densely packed that they form matter of density 60,000, as was computed for the white dwarfs but deemed impossible. That the white dwarf Sirius B was really a very small star—of the size of Uranus—of great mass, hence with a large gravity potential at its surface (20 times that of the sun), was confirmed in the next year by Adams. Einstein had deduced from the theory of relativity that light emitted in such a gravity field had its wavelength changed; Adams, by taking the spectrum of Sirius B, in fact found the wavelength of the lines changed to the computed amount. The certainty that matter of that 60,000 density really existed set new problems to physics; the name 'degenerate matter' indicates how a new department of physical theory had thus been opened.

Continuing Eddington's work, Milne in 1928 investigated more general models of stellar structure, and found some of them becoming unstable and collapsing to a small volume. In such a stellar catastrophe a large amount of gravitational energy is liberated and turned into a heat eruption, an explanation, at the same time, of a nova outburst and of the origin of small O stars of great density such as we find in planetary nebulae; perhaps they are remnants of former novae.

Eddington's work has opened up the interior of the stars to science. The science of astrophysics, i.e. the study of the inner as well as the outer nature of the stars, takes increasing precedence in astronomical investigation. Its latest development is so intimately connected with modern astrophysical problems that it can hardly be treated in an adequate manner as a piece of history.

CHAPTER 41

THE GALACTIC SYSTEM

Do those millions of stars visible through our telescopes and occupying the wide spaces around us form a coherent system? William Herschel had accepted this as self-evident and had connected the system with the visual phenomenon of the Milky Way. From then on, the Milky Way, or rather its central circle, was the basic plane in all researches on the stellar system; its structure was referred to co-ordinates based on this plane, galactic longitude and latitude.

In a primary survey Herschel had traversed these spaces to the farthest limits in a rush; the task of the nineteenth century, while penetrating step by step, was to take complete possession of them. Such research had to go in two directions: investigation of the arrangement of the stars in space and discovery of the laws of their motions.

Spatial arrangement had to begin with surface arrangement over the celestial sphere, taking stock of positions and magnitude. Neither in the mapping of telescopic stars for the search of minor planets nor in the meridian determinations of their exact position was this the deliberate aim of the work. For a real inventory, the precision of meridian work was not needed, and, on the other hand, the catalogues were too incomplete, and the magnitudes treated as secondary were too crude. That they could yet be of some use for this purpose was shown by W. Struve in 1847 in a study of the spatial distribution of the stars based on Bessel's zone catalogue; he derived the rate of crowding of faint stars near the galactic plane compared with their low density at great distances from this plane.

Argelander in Bonn was the first to realize the importance of a good inventory of the stars. His careful and complete cataloguing of the magnitudes of all the naked-eye stars in his first Bonn years has been mentioned above. Now he extended this task to the telescopic stars. He recognized that the method of mapping followed thus far, by alternately looking at the sky and the map and inserting the stars by eyesight, was laborious and inaccurate. So he devised a better working method. The observer, with the telescope motionless, saw all the stars of the same declination successively pass through the field of view. Every time a star passed a line directed north-south and carrying a scale, he gave a signal, the time of which was noted by the recorder sitting in front of the clock; this afforded the right ascension. The observer at the same time noted and called out the scale reading of the passage (affording the declination), as well as the estimated magnitude. Thus a step or zone, in declination as narrow as the field of the telescope but widely extending in right ascension, could be finished in one session. Each part of the sky was covered twice by such zones, so that there was a check and greater accuracy by averaging the two values. Owing to a well-considered limitation of the precision of positions (whole seconds of time in right ascension and 0.1′ in declination) and a wise restriction to ninth magnitude stars (by using a small telescope of only 76 mm. aperture), it was possible to complete the entire northern hemisphere in seven years of work, from 1852 to 1859, during which the enthusiasm of the observers (the assistants Thormann, Krüger and Schönfeld) was able to carry on unabated. From this catalogue, called *Bonner Durchmusterung*, which contains about 324,000 stars (the faintest called 9.5), an atlas of star maps was constructed that surpassed all former maps in completeness and reliability. Both catalogue and atlas in all later years have become indispensable aids in astronomical work. Even now, far within the twentieth century, this old Bonn catalogue has not yet become superfluous for statistical researches.

The name *Durchmusterung* ('survey') was given by Argelander, deliberately to emphasize the coarseness of the positions for the sake of a complete inventory of the stars. It became the international designation for later similar catalogues. First his work was continued by Eduard Schönfeld, his successor at Bonn, to 24° southern declination, in order to include the entire ecliptic with its minor planets. In 1885 Juan Thomé, Gould's successor at the Córdoba Observatory in Argentina, began to extend it over the southern sky, starting with 22° southern declination. He took a somewhat larger telescope, showing stars to the tenth and eleventh magnitudes, so that his programme was larger; when the government grants were later cut so that he had to make all reductions himself, when, moreover, irrigation works in this dry province caused greater cloudiness, his work slowed down considerably. At his death, in 1908, he had only reached the parallel of 62°, though about 579,000 stars had already been observed. And it was not until 1930 that new observers completed the work to the South Pole. Moreover, because of the attempt to keep the estimates adapted to photometric measurements, the *Córdoba Durchmusterung* lacks the homogeneity that is so valuable for statistical discussion.

The Bonn scale of magnitudes is also not entirely homogeneous, since it is based on estimates on a merely mental scale. Exact photometric magnitudes, first provided by the great catalogues of Potsdam and Cambridge, reached only to magnitude 7.5; these have, of course, been used in later statistical work. Photometric measurement of all the hundreds of thousands of *Durchmusterung* stars was an impracticable task, at least visually; photographically, it would be fairly possible, thanks to modern technical methods. In order to make the *Durchmusterung* magnitudes usable for statistical purposes, Pickering measured all the stars within narrow belts of declination 10′ wide, situated at regular intervals, at 0°, 5°, 10° . . ., of declination. By means of these stars the scale of estimated magnitudes could be reduced to the photometric scale for all the separate declinations.

In quite another way J. C. Kapteyn (1851–1922) made an inventory of the southern sky; he used a complete set of photographic plates taken by Gill in Cape Town in 1885–90. To avoid the troublesome reduction of rectangular co-ordinates on the plate to the spherical co-ordinates right ascension and declination, he used a small theodolite which was pointed at a plate placed at a distance equal to the focal distance of the photographic telescope. By setting the theodolite and the plate in the right way it was exactly as if the star field was looked at in Cape Town when just setting. Then the spherical co-ordinates of every star could be read directly on the graduated circles of the instrument, with errors of some seconds of arc only, more accurately than had been done in the visual Bonn catalogue. The magnitudes were derived from the measured diameters of the stellar images by means of empirical formulas. In this way, through ten years of measuring in a small laboratory room at Groningen, the *Cape Photographic Durchmusterung* was achieved, containing about 454,000 stars between 19° southern declination and the South Pole, down to the eleventh photographic magnitude.

The mapping of the millions of fainter stars was possible only by photography. Measuring and cataloguing them all was not necessary, since the maps themselves as reproductions were always at hand. Thus the Harvard Observatory distributed an 'atlas' of all stars to the twelfth magnitude in the form of boxes of glass plates which are copies of the original plates. The slowly progressing co-operative work of the Carte du Ciel has already been mentioned. Making use of the excellent modern optical systems, which produce star images as sharp black points even to the edges of the plate in extensive star fields, Franklin Adams, an English amateur, provided for the needs of the astronomers in a still better way. In 1902–05, first in England and then in South Africa, with a doublet of 10 inch aperture, he photographed the entire sky on 206 plates of 15° square; they were photographically reproduced in maps, where the smallest star points of the fifteenth magnitude can be seen only with a magnifying glass (plate 20). Cataloguing them all with well-reduced magnitudes would be an impossible task.

The *Durchmusterung* catalogues are the basis for statistical studies on the distribution of the stars; first the apparent distribution over the celestial sphere and then the real distribution in space. This field of research was opened by the extensive theoretical and practical work of Hugo Seeliger at Munich, in a series of studies from 1884 to 1909. By means of Pickering's measurements, he derived corrections to the Bonn magnitudes. They varied not only with the declination but also with the star density; in fields full of stars the estimated magnitudes are fainter, and their limit is met at a brighter level—as if the eye were dazzled by their total light, and in the crowding more faint stars are omitted than in poor regions. Working now with fairly correct magnitudes, Seeliger could establish different regularities in the distribution. The number of stars increased in a ratio of 2.8 to 3.4 per magnitude. That every succeeding class comprised three times more stars than the preceding one was a remarkable result; for if space were filled equally with stars, every following class should be four times as numerous, since every next limiting sphere at a distance of $\sqrt{2.5}$ times greater has a volume four times larger. Thus Seeliger concluded as a first result that the space density of stars (number of stars per unit volume) decreases outward at a determinate rate. Of course this is a strongly schematized picture of the universe.

The density, however, is not equal in all directions; the surface density increases towards the Milky Way. This increase is hardly perceptible for the naked-eye stars, and becomes increasingly greater with fainter classes. For Herschel's stars it is far stronger than for the Bonn stars. The same fact can be expressed in another way: the rate of increase of the number of stars with magnitude is small at high galactic latitudes, large at low galactic latitudes, and largest in the Milky Way. This means that in the Milky Way the decrease in star density with distance is small and that it is rapid towards the galactic poles.

These are general qualitative results which do not take into account the diversity of stellar luminosities. This diversity is expressed by the luminosity law, which gives the number of stars (in unit volume of space) as a function of the luminosity. Seeliger brought all these relations into mathematical form and developed formulae expressing the number of stars counted for every apparent magnitude in its dependence on the density distribution and the luminosity law. He demonstrated that, if the star numbers should exhibit a constant rate of increase with magnitude, the resulting decrease in space density could be computed without needing the luminosity law. The counted numbers, however, did not conform to this supposition; the rate of increase

became smaller for fainter classes. Seeliger explained this by assuming that we here arrived at the limit of the stellar system. It is clear, however, that knowledge of the luminosity law is necessary for better results —more generally, that we cannot get complete insight into the structure of our stellar system by mere statistics of star numbers, without making use of the data of parallax and proper motion.

Is there any regularity or law to be discovered in the motions of the fixed stars that can lead us, as with the planets, to the knowledge of spatial structure and controlling laws? A regularity had been detected from a small number of stars by William Herschel: the stars seem to converge towards a certain point in the sky, because the solar system moves in the opposite direction. In the first part of the nineteenth century there was much controversy over this question; Bessel, using an indirect method, could find no solar motion from his more extensive material. But Argelander, then at Åbo in Finland, in 1830 demonstrated with a larger number (390) of proper motions, carefully determined by himself, that Herschel had been right and that the solar system did move towards the indicated apex.

The nineteenth century, in increasing the number of good meridian observations, produced an increasing number of catalogues of proper motions. The most important was, in 1888, the new reduction of Bradley's stars by A. Auwers, made by using modern values for all reduction elements. The Auwers-Bradley catalogue, containing the reliable proper motions of 3,200 stars, remained for many years the basis of all researches on stellar motions, until in 1910 it was superseded by L. Boss's *Preliminary General Catalogue* of 6,188 stars. All computations on the basis of these and other catalogues of proper motion confirmed the results of Herschel and Argelander; the positions found for the apex were all situated in the vicinity of the point 270°, +30° (i.e. right ascension, 270°; declination, +30°). With one exception: when Kobold treated this entire material by Bessel's method, he found an apex far more to the south, near the equator. Bessel's method was based on the situation of the arrows indicating the proper motions, in such a way that forward and backward directions were not distinguished. How it could give a deviating result, indicating some other regularity, remained unknown for a time.

When spectrographic determinations of radial velocity had been made in sufficient number, they were also used to determine the solar motion; besides the direction towards the apex, they could also provide the linear velocity. Campbell derived them in 1901 from 230 stars and again, ten years later, from 1,180 radial velocities measured at the Lick Observatory; the apex found was 268°, +25°, and the velocity 19 or

20 km./sec., comparable to the earth's orbital velocity of 27 km./sec.

So a regularity in the motions of the stars had been found, a general drift towards the anti-apex at 90°, −30°. It was, however, not a motion of the stars themselves but a reflection of the solar motion. Attempts to find systematic regularities in the stellar motions themselves were made in the nineteenth century; thus in 1848 Mädler thought he had found a general motion about a centre of gravity in the Pleiades; but he was mistaken. When freed from the 'parallactic motion' due to the sun's motion, the remaining 'peculiar motions' showed only an irregular chance distribution. Yet another advantage was gained from all this work; because the sun in a century moves a distance 420 times larger than the distance from sun to earth, the parallactic motion of a star in a century is 420 times greater than its parallax. In this way the distance for remote stars could be found, not for single stars, because of their peculiar motion, but for groups, in which, on the average, the chance motions of the separate stars were eliminated.

This method has been used on a large scale by Kapteyn when in the 'nineties he started his researches on the stellar system. He thus derived the main distances of the stars of the third, fourth, and fifth magnitude and found that their rate of increase was less than $\sqrt{2.5}$, which was to be expected from their brightness. This meant that every succeeding magnitude class consists of stars whose average luminosity is smaller than that for the preceding class. Here the astronomers were confronted with the full difficulty of the problem: the distribution of the stars over their apparent brightness is a combined effect of two causes—their different luminosity and their different distance. The problem of how to find the unknown laws of both from their combined effect cannot be solved by any mathematical deduction.

The way in which Kapteyn solved the problem was an admirable piece of practical ingenuity. In 1901 he first computed, from the most reliable sources, average parallaxes for specimens of stars within certain limits of magnitude and proper motion. They were used to derive an empirical formula for the parallax as a function of magnitude and proper motion; such a parallax, expressing the distance, gave at the same time the luminosity. This formula was applied to all the Bradley stars and such fainter stars as had reliable proper motions; their lack of completeness had to be corrected through statistical counts. All these stars could then be distributed in world space by placing them between definite limits of distance, i.e. within successive spherical shells of space. In every shell the stars of different luminosity could be counted; thus Kapteyn could construct a table giving the number of stars between certain limits of distance—hence also for a unit volume of space at different distances—and certain limits of luminosity. The latter afforded

the luminosity law in table form. The table showed that the number of stars increased rapidly with decreasing luminosity, but this increase slowed down more and more for the fainter absolute magnitudes until it ceased for stars a hundred times fainter than the sun, for which the frequency reached a maximum. The numerical values could be expressed by a quadratic-exponential function, in the same way as Gauss's probability law of errors.

We are meeting here a new kind of astronomy, which may be called 'statistical astronomy'. It appears where we have to deal not with stars individually but with hundreds or thousands or even millions of them. Then the nature of the problems has changed with the object; we do not ask which stars, but how many stars have certain characteristics (colour, spectrum, duplicity) or certain values of the parameters (temperature, density, luminosity, magnitude). Counting supplies the measuring. The positions (in the sky or in space) do not matter, but the densities of distribution (over the sky or over space). Statistical laws of distribution are the objects and the working instruments of the astronomer who is dealing with thousands and millions of the heavenly host.

With the knowledge of the luminosity law, the derivation of the spatial distribution of the stars became much easier. Kapteyn took up this problem first, in 1908, by determining the number of stars of every magnitude—or, more precisely, the number per square degree above a certain limit of magnitude—as a function of galactic latitude. He did not restrict himself to reducing the counted numbers of bright stars and *Durchmusterung* stars to statistical data; it was now possible to go down to the fifteenth and sixteenth magnitudes, since photometric measurements of comparison stars for very faint minima of variable stars, made at Harvard and by Parkhurst at the Yerkes Observatory, had extended the scale of reliable magnitudes to this faint limit. It was clearly shown by these figures that the rate of increase in the number of stars per square degree for the fainter magnitudes lessened greatly in these classes. It could also be rendered fairly well by a Gaussian curve, different, of course, for different galactic latitudes. Schwarzschild in an ingenious analysis showed how the density function (space-density dependence on distance) could be directly derived from the star-number function (dependence of the number of stars on magnitude) and the luminosity function, if all three could be represented exactly by Gaussian probability functions.

The distribution derived by Kapteyn consisted in a density nearly constant around the sun up to a distance of 100 parsecs, then continuously decreasing rapidly towards the galactic poles, slowly in the galactic plane. The surfaces of equal density were strongly flattened ellipsoids of revolution, so that we may speak of an 'ellipsoidal distribution' of the stars. In the next dozen years computation at the Groningen Astronomical Laboratory gave more accurate numerical results: a density of $\frac{1}{16}$ the central density around the sun was found in the galactic plane at 3,500 parsecs and towards the poles at 660 parsecs.

That Kapteyn's stellar system had the figure of an ellipsoid of revolution was not a result but a presupposition; since in this first approximation differences along galactic longitudes were neglected and averaged, and only the variation with latitude was considered, the result was identical for all longitudes. Thus the Kapteyn system was a strongly schematized and smoothed picture of the stellar universe. It was schematized also in the variation of density with distance; because the luminosities of the stars were widely different, what was visible in the broad figure of the luminosity curve, all short-range variations of space density with distance, were smoothed out and barely perceptible in the distribution of the stars over the apparent magnitudes.

The Milky Way was spoken of here as a luminous belt around the sky or sometimes as a plane or layer of stars in space. Now it must be viewed as a proper object of study. What really is the Milky Way? Exactly speaking, it is a phantom; but a phantom of so wonderful a wealth of structures and forms, of bright and dark shapes, that, seen on dark summer nights, it belongs to the most beautiful scenes which nature offers to man's eyes. It is true that its glimmer is so faint that it disappears where the eye tries to fix upon it—it is perceived only by the rods, not by the cones of the retina, hence is seen only by indirect vision; yet, when all other glare is absent, it gives an impression of brilliant beauty.

It was mentioned earlier (p. 158) that Ptolemy in his great work gave a description of its course and irregularities. It is a remarkable fact that in all later centuries no attempt was made to repeat and improve his work and to depict the phenomenon as it appeared to the eye. Star maps mostly showed a worthless picture of a uniform, sharp-bordered river. Probably the reason is that what always remains the same does not attract the attention. John Herschel, when he was making observations at the Cape of Good Hope in 1834–38, was the first to be so strongly struck by the uncommon sight of the southern part of the Milky Way not visible in Europe that he was induced to make a sketchy picture of it. After Argelander, in his appeal to amateur astronomers, had pointed to the Milky Way as one of the objects of study, it was taken up by Julius Schmidt in Athens and by Eduard Heis in Münster. The latter, in his atlas of the northern sky, published in 1872, gave a drawing of the Milky Way. Gould had his assistants Thomé and Davies do the same for the southern Milky Way on the maps of the *Uranometria Argentina*. In both cases the Milky Way was an accessory feature inserted on maps

where the stars were the chief objects; this is also shown by the lack of well-elaborated fine details. More detailed drawings in two publications devoted to the Milky Way as sole object appeared at the end of the nineteenth century shortly after each other—one in 1892 by O. Boeddicker, assistant to Lord Rosse at Parsonstown, Ireland; the other in 1893 by C. Easton, a Dutch amateur at Dordrecht. These pictures, as well as later ones, though presenting considerable differences in the mode of conceiving and depicting the details, agreed in showing how intricate an object it is. Where a superficial view showed only a broad luminous band, attentive study revealed a sequence of irregular clouds and patches, connected by light streams of various intensities, separated by and mixed with dark fissions and interruptions. Yet there was a regularity visible in its general appearance, in that at one side of the sky it is far brighter than at the opposite side. The brightest light patches are seen in Sagittarius, at galactic longitude (reckoned from the intersection point with the equator in the Eagle) of 330°. On both sides the brightness decreases, though rising again to secondary maxima in the Swan (at 40°) and in the Ship (at 260°); in Perseus (at 120°) only a faint glimmer is visible.

After this difficult visual work, the application of photography was a revelation (plate 21). In 1869 several astronomers—H. C. Russell in Sydney, Max Wolf in Heidelberg, and E. E. Barnard at the Lick Observatory—began to photograph the Milky Way—as well as comets, with lens systems of great angular aperture, mostly 1 : 5, to have a great surface brightness. After about three hours' exposure there appeared on the plates the bright cloud forms of the Milky Way in great intensity and with a wealth of detail that never could have been detected by the eye, no matter with what optical aid. In 1891 Max Wolf published beautiful pictures of a bright nebula near Deneb in the Swan that, from its peculiar form, was called the America Nebula. Barnard used increasingly better instruments, but finally a 10 inch doublet of 1 : 5 obtained with the aid of a grant by Miss Catherine Bruce. He employed it to photograph all the parts of the Milky Way visible in the United States; his pictures are reproduced in an atlas published in 1927 after his death. Still more perfect was the Milky Way atlas of Frank Ross, expert constructor of optical systems, who devised one that pictured fields more than 20° in diameter, with the stars shown as sharp, fine points up to the edge. It is to be regretted that completeness of this atlas failed by the omission of the most southern part, between longitudes 240° and 300°.

What all these photographs revealed was, first, that the real Milky Way, the bright clouds and streams, was made up of hundreds of thousands of very faint stars, from the thirteenth, fourteenth, and fifteenth magnitudes downwards. They were situated at great distances, between 1,000 and 10,000 parsecs, where Kapteyn's stellar system faded out in more and more thinly populated outer parts. The small densities computed for his schematized universe were deceptive averages of large, nearly empty spaces and restricted realms of great density. In those outer spaces large condensations of stars occur, similar to, or even larger than, the central parts up to 500 parsecs of Kapteyn's system, now mostly called the 'local system'. What we see as the Milky Way surrounds it at far greater distances. So it was not inappropriate that Proctor in 1869 conceived the Milky Way as a sinuous ring surrounding our solar regions at a great distance. Easton, in a series of studies in 1894–1900, transformed it into a spiral structure, with the great Cygnus cloud, between β and γ Cygni, as its nucleus and the sun situated in one of the spiral arms. Such theories were hypotheses of what might be. The problem of what really is could only be solved by deriving spatial densities from extensive counts of stars.

The second conspicuous phenomenon in the Milky Way photographs, giving them their most picturesque aspect, were the dark features, empty spaces almost without stars, often sharply defined. They appeared in all dimensions between very large and very small, in the most freakish shapes, such as patches, canals and lanes interposed between the bright star masses. Barnard gave much attention to them and in 1919 published a catalogue of 182 dark objects, afterwards increased to 352—objects, indeed, because they must be dark clouds or structures of absorbing matter extinguishing the light of the stars behind them. The biggest were already known from visual observations: the famous Coalsack near the Southern Cross, some dark spots in the Swan, and an almost black, starless space south of θ Ophiuchi. In former times they had been considered as empty spaces, interrupting the star-filled spaces and separating the single star clouds, just as did the great dark rift separating the two branches of the Milky Way from Centaurus to the Swan. The small black spots on the photographs, however, could not be explained in this way.

Outside the Milky Way also and at its borders, regions with a lack of stars were found. On Schönfeld's atlas of the Southern Bonner *Durchmusterung* a large irregular part of Ophiuchus with a great deficiency of stars is seen. On the Franklin Adams maps a number of irregular, mutually connected voids is seen in Taurus. Dyson and Melotte at Greenwich in 1917 published a drawing of them; they concluded that the dark nebulae causing the lack of visible stars were no farther distant than 100–200 parsecs. Later investigations of other astronomers confirmed this result; the great Ophiuchus Nebula, causing a scarcity even of naked-eye stars, is at nearly 100 parsecs or less. For smaller dark spaces between the galactic clouds, distances of 400–500 parsecs have been found. So these dark nebulae may be compared with clouds and threads of smoke or dust, of world dimensions, surrounding us at close distances, and obstructing our view of the far distant galactic star accumulations that can show their full splendour only through the interstices.

Related to the Milky Way are the various kinds of nebulae and star clusters. Leaving aside the gaseous nebulae treated above (p. 451) and also the two Magellanic Clouds near the South Pole that look like small, detached bits of Milky Way, there remain three kinds, all consisting of stars, as is shown by their continuous spectrum. Among the 5,000 nebulae collected in 1864 by John Herschel in his *General Catalogue* and the 13,000, to which, in 1888, Dreyer increased this number from many sources in his *New General Catalogue* (*N.G.C.*), the great majority consisted of so-called 'unresolvable' nebulae, in which separate stars could not be detected with the largest telescopes. They often showed a spiral structure, first discovered by Lord Rosse, so that the entire class was sometimes designated as 'spiral nebulae'. They were found to accumulate around the galactic pole, in the constellation Coma and surroundings, and hence to stand in a kind of antagonism to the stars. A second kind consisted of the nearly one hundred so-called 'globular clusters', where good telescopes showed the outer borders crowded with numberless small stars, which, still more strongly condensed in the central parts, formed an unresolvable bright mass. They are all situated on one side of the sky, in the hemisphere having its centre in Sagittarius. Then, as the third kind, we have the 'open clusters', loose, often irregular, groups of stars, mostly in the Milky Way, from large groups like the Pleiades and Praesepe in the Crab, descending in size and brightness to small clusters of petty stars. Obviously the open clusters are nearest, the spirals most remote.

When Trumpler, at the Lick Observatory, investigated the open clusters and the spectra of the separate stars therein, to derive the distance, he found in 1930 that the relations perceived between the stellar magnitudes and the sizes of the clusters could be explained only by assuming a general absorption in space; such an absorption diminishes the brightness of the stars but not the size of the cluster. His result was confirmed by Van de Kamp at the Sproul Observatory and by others, from the reddening of distant stars. It is well known that small dust particles and gas molecules scatter the light more strongly the shorter the wavelength; hence the blue colour of the sky at daytime and the reddening of far-distant stars, whereby they show redder than corresponds to their spectral class. Such a general absorption in the star-filled galactic layers can explain the apparent accumulation of spiral nebulae at the galactic poles. Photographs taken by Hubble at Mount Wilson show tens of thousands of minute nebulae outside the galactic zone, between the star images, whereas they are entirely missing in the Milky Way, being extinguished by the absorbing matter which extends somewhat irregularly over the middle layers of the Galaxy. Probably the separate dark nebulae noted above, among them the extensive absorbing nebulae in Taurus and Ophiuchus, are nothing but the nearest and densest parts of the absorbing matter that fills all space between the stars. The occurrence of these formerly unknown irregular absorptions makes the derivation of the space density from the observed numbers of stars far more difficult.

Thus the galactic system appears to consist not only of millions of stars but, in addition, of absorbing matter occupying the space between them. The study of this matter, the nature and the size of the different solid particles of which it consists, was a new and important field of astrophysical research. It is not the only substance filling these spaces. In 1904 Hartmann discovered that in the spectrum of δ Orionis, which has a strongly variable radial velocity, the K line of ionized calcium remained unmoved and hence was produced not in the stellar atmosphere but in outer space. Other different stars showed the same phenomenon. So ionized calcium atoms roam freely through interstellar space like an extremely rarefied gas. Later, in 1919 and thereafter, other atoms, e.g. of sodium and ionized titanium, were noticed. These thin gases do not show the irregular distribution of the solid absorbing particles; instead, they exhibit small radial velocities, indicating currents in world space.

We must now return to the motions of the stars. When Kapteyn started his investigations of the stellar system, he intended to base them not upon the magnitudes but on the proper motions of the stars, because the velocities were far less different than the luminosities. So he tried to establish a law not of luminosity but of velocity. But the proper motions were refractory; they did not fit in with his scheme of formulae; so he had to proceed the other way. For several years the singular behaviour of the proper motions worried him, until he found the solution, which he presented first in 1904 at the astronomical meeting in St Louis, Missouri, and then in 1905 to the British Association meeting in Cape Town: the theory of the two star streams.

If the velocities of all the stars are represented by arrows from one origin, the points of these arrows form the velocity diagram; the density of these points indicating the frequency of the velocities was found to decrease from the centre outward. As a consequence of the solar motion in space these velocities must show a preferential direction of their proper motions, pointing towards the anti-apex. Kapteyn found that in each region the proper motions showed *two* preferential directions, pointing towards two different goals, which he called the apparent 'vertices'. They can be thought to be produced by a combination of the solar motion towards the apex and the motion of the two parts of the totality of stars relative to their common centre of gravity; the latter, then, must take place in opposite directions, towards the true vertices opposite each other, found at 91°, +13°, and at 271°, −13°. These were near the directions once found by Kobold by means of Bessel's method. Kapteyn's result was confirmed by a more extensive investigation in 1907 by Eddington, whose diagrams of velocity distribution, because of their curious shapes, became known as 'Eddington's rabbits'. At the same time, Schwarzschild showed by a careful theoretical analysis that the phenomenon could be described quite as well in another way, viz. as an ellipsoidal distribution of velocities in the region examined. The surfaces of equal density in this diagram, according to Schwarzschild's theory, were not spheres but ellipsoids, elongated in the direction of the true vertices, which is the most frequent direction of velocities. Of course it appeared, on further research by different astronomers, that the phenomenon was more complicated; there were diverse groups of stars showing special stream motions. But the main phenomenon was ascertained; a regularity had been found in the stellar motions, and the question now was how to account for it. Kapteyn supposed that the galactic system was a mixture of two kinds of stars rotating in opposite direction, so that its flat shape was explained without rotation of the

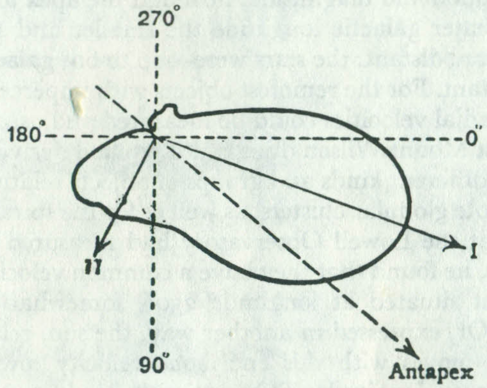
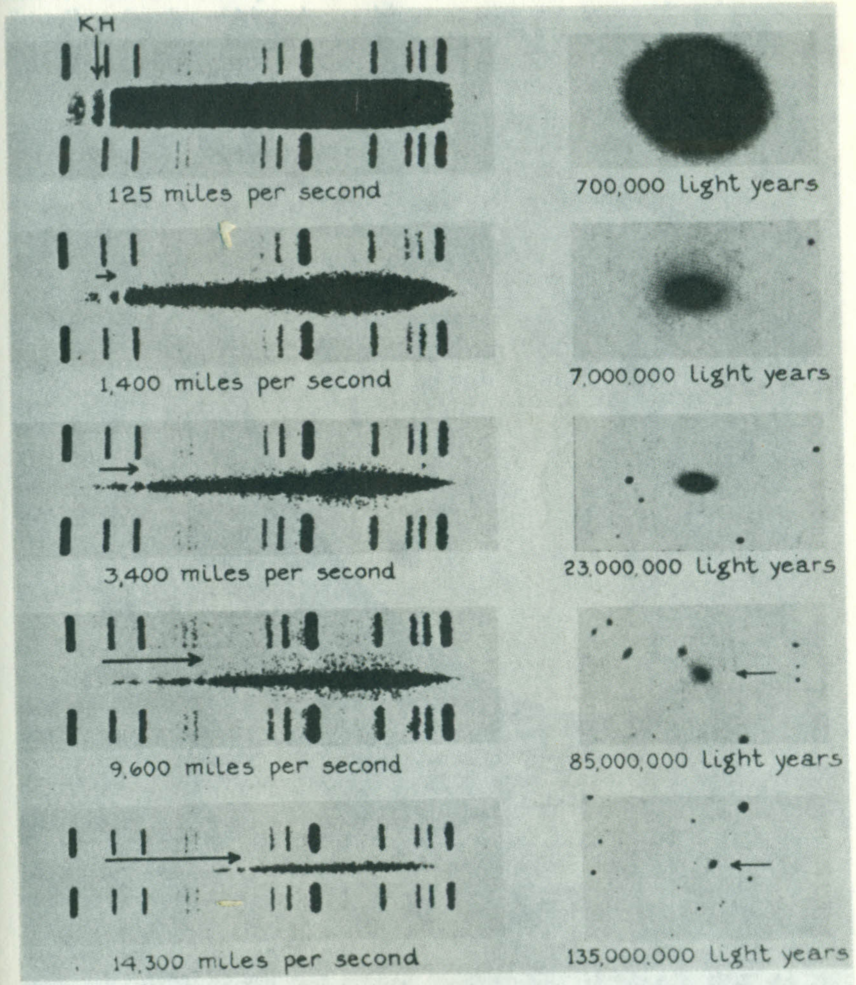


Fig. 36

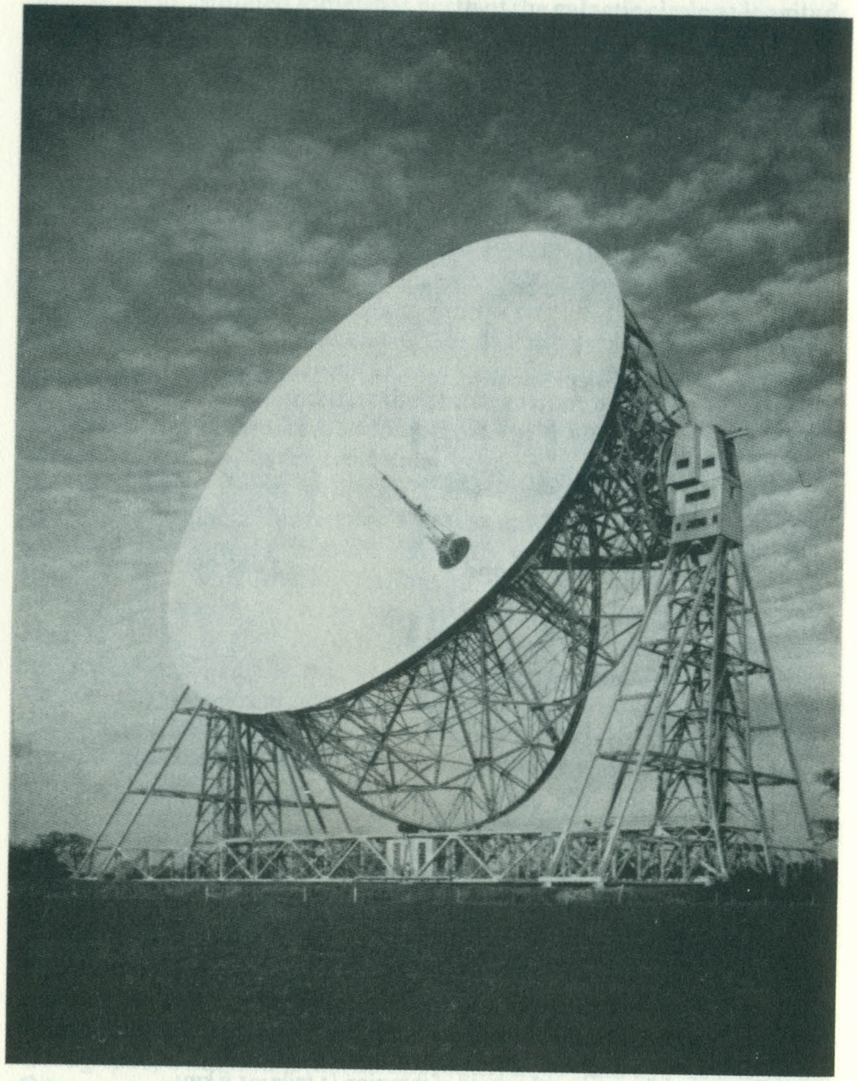
entire system. The true explanation would afterwards be found to be quite different.

Not all computations of the solar motion resulted in the same apex at 270°, +30°, situated somewhat north of the galactic circle at longitude 23°. If certain star groups have a special motion relative to the main system, it will appear in a different solar motion computed from them. In 1896 Stumpe derived the solar motion from groups of stars separated according to motion and magnitude; he found the apex to be the more displaced to greater galactic longitude the smaller and slower, hence probably the more distant, the stars were—up to 60° galactic longitude for the most distant. For the remotest objects with imperceptible proper motions, only radial velocities could be measured and used. In 1923–24 G. Strömberg at Mount Wilson discussed them and derived the motion and velocity of different kinds and groups of objects relative to the sun. For the far-remote globular clusters, as well as for the spiral nebulae, for which Slipher at the Lowell Observatory had measured a number of radial velocities, he found that they have a common velocity of 300 km. towards a point situated at longitude 250°, somewhat south of the galactic circle. Or, expressed in another way, the sun, relative to these distant objects, moves with this enormous velocity towards another apex at 70° galactic longitude. This motion it has in common with all the stars surrounding it and relative to which it has only the small velocity of 20 km. Another curious phenomenon was presented by a number of 'racer stars', showing abnormal velocities above 60 km. and even up to more than 100 or 200 km. They were all found to move toward one side of the sky, centred about longitude 234°, with none moving to the opposite side. If we should adopt the system of the distant clusters and nebulae as the stationary zero point of the universe, these apparent racers would be the idlers among the rapidly moving bulk of the sun's companions.

The stars of spectral type B, which are almost all situated in the Milky Way, did not show the two streams. They presented another phenomenon, the so-called 'K effect', all wavelengths being too large. This was shown afterward to be a relativity effect of the strong gravity field at their surfaces due to their great masses. In 1922 Freundlich and Von der Pahlen at the Einstein Institute at Potsdam found that, superimposed on this K effect, the radial velocities presented a periodic variation with galactic longitude, a maximum of recession at 0° and 180° of longitude, a minimum (i.e. an approach) at 90° and 270° of longitude. Other stars with small proper motions, hence probably also at a great distance, showed the same fluctuation. Then J. H. Oort in 1927 at Leiden, proceeding from theoretical studies of Lindblad on rotating stellar systems, deduced that in the case of a rotation of the entire galactic



23. Radial speeds of nebulae (according to E. Hubble, *The Realm of the Nebulae*). The displacement of the doublet H and K (breaks in continuous spectrum indicated by the arrow above the spectrum) determines the speed of recession (1 mile = 1.6 km; 1 light year = 1/3¼ parsecs) (p. 488)



24. The Jodrell Bank Radio Telescope

system about a centre in Sagittarius, where the densest star clouds are situated, just such a periodic alternation of positive and negative radial velocities must present itself. If the sun and the surrounding stars describe circular orbits about this attracting centre as the planets do about the sun, the stars nearer to the centre will have a greater, and those farther from the centre a smaller velocity than the sun. In the first case the preceding stars are escaping from the sun, the following ones overtaking it; in the second case the forerunners are overtaken by the sun, the after-runners left behind. So, as figure 37 shows, they will exhibit radial velocities alternating with their position relative to the sun and increasing with the distance to the sun. Considering the velocity of 300 km. toward 70° galactic longitude, nearly perpendicular to the direction of the Sagittarius star clouds at 330° longitude, as the orbital velocity of the sun and its stellar surroundings, we will have the stars about 0° and 180° longitude receding from the sun, the stars about 90° and 270° approaching it, both perceptible only at distances of some hundreds of parsecs.

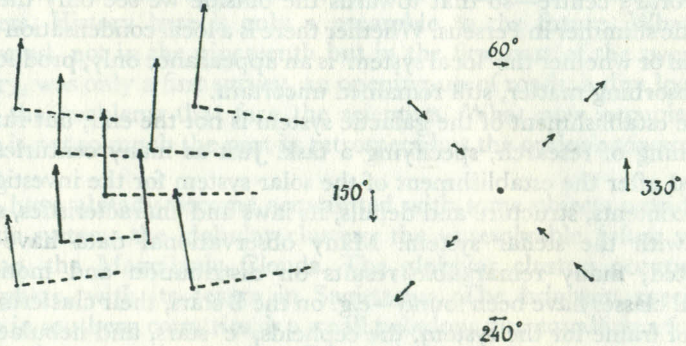


Fig. 37

Thus the galactic system was shown to be a rotating system. Oort worked out its theory in detail; he found its centre to be at a distance of 6,000 parsecs with a central attracting accumulation equal to 60,000 million solar masses, whereas an equal mass is dispersed over the entire system; for a complete revolution, the sun needs 140 million years. When the stars surrounding the sun have motions deviating by chance from exact circles, their velocities relative to the sun, as Oort demonstrated, will show a preferential direction toward the centre. Since this deviates by only 20° from the preferential direction derived by Schwarzschild (Kapteyn's vertex), star streaming, though with a small irregularity, here found its explanation. Lindblad computed the distance to the centre to be 9,400 parsecs, and the sun's period of revolution to be 200 million years. J. S. Plaskett and J. A. Pearce at the Victoria Observatory found from their spectra of B stars that the interstellar gas takes part in the rotation.

The main features of the stellar system to which our sun belongs, its shape and its state of motion, are now established as far different from what had been found in Kapteyn's pioneering investigations. We may call it the 'galactic system'; what we see as the wonderful shapes in the shining light band of the Milky Way, what appears on the photographs as brilliant star clouds, consists of the thousands of millions of stars of this system. But, partly covered and obscured by gigantic dark streaks of absorbing matter, the dense central masses are visible to us only in small parts in the bright galactic clouds of Sagittarius. Our sun is not situated near the centre but far away, somewhere in the border parts—as with the Copernican revolution, another inroad on human pride as the world's centre—so that towards the outside we see only the faint galactic shimmer in Perseus. Whether there is a local condensation about the sun or whether the 'local system' is an appearance only, produced by the absorbing matter, still remained uncertain.

The establishment of the galactic system is not the end, but rather a beginning of research, specifying a task. Just as many centuries were needed after the establishment of the solar system for the investigation of its contents, structure and details, its laws and characteristics, so it is now with the stellar system. Many observational data have been collected, many remarkable results on distribution and motion of special classes have been found—e.g. on the B stars, their clustering as a kind of frame for the system, the cepheids, 'c' stars, and nebulae. The elucidation of all the problems of structure presented by the system of stars and by the dark matter, as well as of their origin and development, is a tremendous task for future research.

CHAPTER 42

INTO ENDLESS SPACE

Our solar system, so large compared with the earth and larger still compared with our surroundings and ourselves, is now included as a petty particle in the greater galactic system, millions of times larger and consisting of thousands of millions of suns, the extent and the dynamics of which we have now come to discover. But the galactic system is not the entire universe. What is found outside it? With this question we enter into a new field, a third platform in the investigation of cosmic space.

Here we are faced with another state of affairs than in the previous chapters. History here is only a preamble to the future. What was discovered, not in the nineteenth but in the first part of the twentieth century, was only a first survey, an opening-up of roads, a dim looming up of the problems that face the scientists. What now occupies our minds is not so much the past in retrospect but the outlook towards the future.

We have already become acquainted with some objects outside the galactic system: the globular clusters, the unresolvable (often spiral) nebulae, the Magellanic Clouds. The globular clusters occupy one hemisphere, with its centre in Sagittarius. The brightest specimen, visible in southern countries, is a small nebulous disc equalling a fourth-magnitude star and named ω Centauri. In northern countries some smaller ones can be seen, just visible to the naked eye as sixth-magnitude stars; they are designated by their Messier numbers, M13 and M92 in Hercules and M5 in Serpens. The Large and the Small Magellanic Clouds, near the South Pole, look like detached pieces of the Milky Way, at 33° and 44° galactic latitude. John Herschel, at the Cape, found them to consist of a dense accumulation of stars, clusters, gaseous and other nebulae, which he catalogued.

In 1895 Bailey at Harvard Observatory, studying a number of photographs of the globular clusters M3, M5, and ω Centauri, discovered in their outer parts a large number of variable stars. Afterwards the same was found for some thirty other clusters. Most of these variables have periods of about half a day, but periods of several days also occur.

It appears that all of them belong to the cepheid class, and their periods and light curves could be determined from a large number of plates. Then such variables were found in the Small Magellanic Clouds also; and in 1912 Miss Leavitt at Harvard discovered in them an exact correlation between their period and their medium brightness (the average of maximum and minimum magnitude). The brighter they are, the slower their pulsations. For a period of 2 days the medium magnitude was 15.5; for 5 days, it was 14.8; for 10 days, 14.1; for 100 days, 12.0. Since the difference between apparent and absolute magnitude is the same for all the stars in such a Cloud, this means that for cepheids generally the period varies in a regular way with the luminosity. This law could not have been found from the cepheids in our galactic system, because they are situated at different unknown distances. Assuming that this law holds for cepheids in general, Hertzsprung in 1913 was able to fix the scale of their luminosities. From the small proper motions of 13 galactic cepheids between the second and the sixth magnitudes, reduced to equal distance, he could derive their parallactic motion and hence their mean parallax and luminosity. He found that a medium absolute magnitude of −2.3 belonged to a period of 6.6 days. Miss Leavitt gave for this period a photographic magnitude in the Cloud of 14.5, corresponding to 13.0 visually; so the apparent magnitudes were 15.3 magnitudes fainter than the absolute magnitudes. This meant that the distance of the Small Magellanic Cloud was 11,000 parsecs. Afterwards it became evident that the scale of magnitudes for the faint southern stars was considerably in error; a repetition of the computation with better data by Shapley in 1918 modified the distance to 29,000 parsecs, larger than the dimensions of our galactic system.

In this way the cepheid variables afforded the yardstick with which to measure distances in celestial space. 'Lighthouse' stars they had been called by Jeans on account of their periodical flaring up; now indeed they were found to be beacons to guide the astronomers into the far depths of space. Shapley used them first in his discussion of the photographs of globular clusters, which he had taken from 1916–17 with the 60 inch telescope at Mount Wilson. He measured the photographic and photovisual magnitudes of the brightest as well as of the variable stars in these clusters; the latter afforded him their distances. He found that the brightest stars were red and were $1\frac{1}{2}$ magnitudes brighter than the numerous cepheids of $\frac{1}{2}$-day period and, hence, that they were supergiants. He found, moreover, that the smaller the size of the clusters, the fainter were the stars and the fainter also was the total brightness of the cluster, as determined formerly by Holetschek in Vienna. This meant that all the globular clusters are built on the same plan and that their different aspects are due to different distances. These distances could now be derived for all the 86 globular clusters: for the brightest and nearest from the cepheids, and for the smaller ones from apparent diameter and total magnitude. The nearest is the bright ω Centauri at a distance of 6,500 parsecs, the most remote is a cluster of magnitude 9.7 at 67,000 parsecs. They occupy a large space, situated on one side of us, with their centre at 20,000 parsecs towards longitude 325° in Sagittarius. In the central plane of the galaxy they are lacking, evidently through the strong absorption in this plane. Though they are situated outside the galactic system of stars, Shapley considered them as belonging to this system as a kind of environment. His work was the first clear indication that the galactic system extended far more towards Sagittarius than had formerly been assumed. In 1921 he even estimated its total size to be 100,000 parsecs, far greater than would correspond to Cort's later result of the centre at 6,000 parsecs. The figure is certainly too large, perhaps because the weakening by the absorbing matter of the light of the remotest clusters has not been taken into account. The two Magellanic Clouds at distances of 26,000 and 29,000 parsecs and with diameters of 4,000 and 2,000 parsecs constitute kinds of satellites of the galactic system.

The next problem was to find out where the unresolvable nebulae were situated, outside or inside the galactic system. The prevailing opinions may be learnt from a discussion which took place in 1921 between Harlow Shapley and Heber D. Curtis on 'The Scale of the Universe'. Curtis held that they were 'island universes', separate stellar systems outside and comparable to the galactic system, which he assumed to be no larger than 10,000 parsecs. He criticized Shapley's exact luminosity-period relation for the cepheids and the distances derived therewith; on this point, however, he was not successful. Shapley on the other hand, pointing to the accumulation of the spirals at the galactic poles, considered them not as distant galaxies but as belonging to our galactic system, itself regarded as larger, a 'continent universe'. The fact that no stars were visible in these not very distant nebulae, though the spectrum was continuous, he ascribed to strongly scattering nebulous matter within them; and he held as a tentative hypothesis that the 'spirals' are not composed of typical stars at all but are truly 'nebulous objects'.[213] His chief argument, however—their accumulation at the poles and their absence in the Milky Way—lost its validity when it was found to be only an appearance produced by the absorption in the galactic plane.

Gradually the number of these nebulae had increased. To the 13,000 of Dreyer's *New General Catalogue* of 1888 the photographs of the sky studied by Max Wolf and by Palisa (for the purpose of finding planetoids) had first added many thousands; the Franklin Adams maps and

Harvard plates increased them still more, with ever smaller items. Were they really small objects, or was the apparent smallness due to their distance? Gradually the latter opinion became dominant. Yet they were not built exactly on the same model. Among the large specimens, round or flattened, many show a smooth brightness distribution, decreasing to the border; others are spirals, either with large spiral arms extending from a small nucleus or with narrow windings closely serried around a broad body. They can be seen in their true shape when viewed from right above (as the oft-pictured beautiful M33 in the Triangle and M99 in the Hounds). Others viewed obliquely appear strongly flattened like the largest among them, the great Andromeda Nebula, M31, the spiral arms of which were first shown on photographs taken in 1890 by Isaac Roberts (plate 22).

In 1885 a new star, a nova of the seventh magnitude, appeared in the bright central parts of the Andromeda Nebula. It was possible that by mere chance an ordinary nova had appeared right in front of the nebula; but a connection was thought to be probable. In later years, when large-scale photographs of its outer parts were made, a number of stars were found that suddenly appeared and soon decreased more slowly to invisibility, just as do our ordinary novae. Their maximum brightness, however, was no more than the fifteenth to eighteenth magnitudes; therefore, if they are stars like our own novae, the nebula must be very far away. In the years 1919–26 Hubble made a large number of long exposures with the 60 inch and the 100 inch at Mount Wilson, especially of the outer parts and the spiral arms, of the Andromeda Nebula as well as of M33. On these photographs the nebulous light was at last resolved into an abundance of extremely small stars. Careful examination revealed, besides 67 novae in the Andromeda Nebula, about 40 cepheid variables in both. Their periods were between 10 and 80 days; their magnitude at maximum was 18–19; the minima were below the limit of visibility on the plates, which also explains the absence of cepheids with short periods. The long-period maxima, however, were sufficient to establish their distance. Comparison with the Small Magellanic Cloud indicated that M33 was nine times more remote, hence at a distance of 260,000 parsecs, and the Andromeda Nebula at 275,000 parsecs. The diameter of the former, then, is about 5,000, and of the latter about 14,000 parsecs.

Thus it was settled that at a distance of some hundreds of thousands parsecs other stellar systems are found entirely comparable to our galactic system. Other galactic systems appearing to us as spiral nebulae occupy the far spaces around. How far? There is no reason to suppose that only our nearest surroundings should be thus favoured; moreover, numerous smaller nebulae are found in our catalogues. At a 10 times

greater distance they must look 10 times smaller and 5 magnitudes fainter; so the nebulae down to the tenth or eleventh magnitude must occupy space up to three million parsecs.

These are brightest ones only. Now that nebulae had become objects worthy of study, a systematic search was made. Pickering in former years had large plates taken with long exposures. Shapley, his successor in 1921 at Harvard Observatory, had them closely examined by Miss Ames to discover and catalogue all the minute nebulae hardly distinguishable from the thirteenth- to sixteenth-magnitude stars. In their thousands and tens of thousands they now appeared, the remote galactic systems occupying ever wider depths of space, at distances of 20, 30 and 50 million parsecs. The systematic survey comprising 60,000 of the smallest nebulae, made by Hubble at Mount Wilson, has already been mentioned.

The space explored by astronomy thus increased immensely, and the number of galactic systems therein might be estimated at hundreds of thousands. 'A galaxy of galaxies', they were called by Shapley. They were not distributed evenly or at random, but mostly condensed in groups or accumulations. The condensation about the galactic pole of rather bright near spirals had already attracted attention in the nineteenth century; now fainter groups appeared in different parts of the sky. Within each group there were differences in dimension; Shapley estimated our own galaxy to be one of the biggest. A 'luminosity function' could even be established for such groups and used in the derivation of distances. Evidently in this greater world, too, there is structure.

Now the question arises: Can we go on indefinitely in this way? In infinite space 50 million parsecs does not mean more than 1 parsec or 1 inch. But is space infinite? Since Gauss's speculations on the axioms of geometry, in the first years of the nineteenth century, and Riemann's discussion of non-Euclidean forms of space, in about 1854, most scientists think that we cannot be sure about the absolute validity of Euclid's geometry for our world. There might be a small deviation towards a Riemann geometry, in which parallels intersect at great distances, the sum total of the angles in a triangle exceeds 180°, and space, though unlimited, is not infinite. Analogy with the case of two dimensions, where the plane is replaced by a spherical surface, introduced the term 'curvature of space'; if it is small, the deviations from Euclidean space are perceptible at great distances only. Our galactic system is too small to show any deviation; in the thousand times larger system of galaxies, indications might appear in the apparent distribution, for instance, in a diminishing increase of their number for fainter classes.

However, on account of unexpected new discoveries, the treatment of these questions was abandoned or rather included in new and wider problems. We spoke previously of the spectrographic measurements of the radial velocities of globular clusters and the brightest among the spiral nebulae, from which the sun's orbital velocity of 300 km. was derived. Deviations of hundreds of kilometres remained as peculiar velocities of the separate objects. Slipher at the Lowell Observatory and Pease at Mount Wilson in 1916–17 measured the radial velocities of a number of fainter nebulae to increase the body of data. In 1919 Shapley pointed out that the remaining peculiar velocities were all positive and hence that the nebulae were moving away from us; but he could not make out where to look for an explanation. In 1929 Hubble demonstrated that the velocity of recession regularly increased with the distance of the object (pl. 23). To test this correlation, it was necessary to photograph the spectra of faint nebulae of the fourteenth to eighteenth magnitudes: all the light falling on the 50 square feet of the 100 inch aperture was condensed into a small spectrum $\frac{1}{10}$ inch long. The only lines visible in such a continuous spectrum (a mixture of chiefly second-type stars) were the H and K doublet of ionized calcium and sometimes the G group and Hγ. They stood far to the red of their true places, displaced tens or even hundreds of Ångstrom units, indicating outward velocities of tens of thousands of kilometres. The greatest velocity measured in 1936 was 42,000 km. for a nebula of magnitude 17.9, the brightest in a group in Ursa, whose distance was estimated at 72 million parsecs.[214]

This discovery that the far galaxies are receding with velocities increasing with distance—500 or 600 km./sec. per million parsecs—presents such a curious and strange phenomenon that it upset all our former concepts of the universe. It does not mean that our galaxy is resting in the centre of the universe; it means that this universe of galaxies is expanding uniformly, so that all its members are receding from one another. Since 500 km. per second is identical with 0.52 parsec per 1,000 years, the rate of yearly expansion is $\frac{1}{2000000000}$ of the present distance. If we assume that every galaxy has always kept its present linear velocity, it follows that two thousand million years ago all these galaxies were in a pile, close together.

Here, all of a sudden, we face a date in the remotest past that never could have been suspected. In all more or less fantastic cosmogonic theories, embodying strong extrapolations from present-day processes, a rather regular development was presupposed to be extensible indefinitely into the past. This provoked, however, some uneasiness, of the kind which always arises when we recklessly venture to speak of the infinite. Now, however, we are unexpectedly faced with an initial date, not precisely of a creation, yet of a starting point of the present development, beyond which we cannot see farther into the past.

This is based, it is true, entirely on the assumption that the velocity of each galaxy has always and forever been the same, which is in accordance with our fundamental mechanical 'principle of inertia', but without absolute certainty. And it must be added that far greater periods of time had been assumed for the evolution of the separate stars. Now, however, attention was directed to other phenomena pointing in the same direction. The percentage of radioactive matter in minerals and meteors, compared with the known rate of decay, points to a date of origin of about a thousand million years ago. The open clusters in our galactic system are supposed to have developed from denser accumulations, which, by the attraction of other stars, have gradually been dissolved; this must have been going on during a finite time of the same order of magnitude. The equipartition of energy—the fact that stars with the greatest masses have the smallest velocity—not yet completely realized, can be explained by the mutual attraction of the stars only if in former times they were more closely packed. All these considerations, though they form no strict proof, pointed to the same conclusion: that the present development started a couple of thousand million years ago, when the galaxies and perhaps the stars also were much nearer to one another. Or, expressed in another way: that an originally united system had been torn to pieces by a kind of explosion, whereupon the fragments, with different constant velocities, began their journey toward infinity. Thus in the picture of a uniform past, gradually fading into the distance, appeared a break, a special moment, that brought contrast and pattern into history. It is true that it is full of inconceivable mystery, but it invites further researches.

The discovery of the retreat of the galaxies came at a time already filled with profound discussions on space and time. Einstein's general theory of relativity, formulated in 1916, reduced gravitation to local curvatures, produced by matter, in the four-dimensional space-time pattern. Through the totality of attracting matter, space must have a positive curvature, i.e. a finite content. The formulae deduced by Einstein and by De Sitter showed that a space cannot be in stable equilibrium; according to the theoretical solution give in 1927 by the Belgian scientist Lemaître, the curvature must change continuously. Combined with the observed behaviour of the galaxies, it led to the theory of the 'expanding universe'. In this conception the material elements of the universe, the galaxies, are diverging not through their own motion but because space, in which they are embedded, is expanding—in two-dimensional space the same would happen with points on an expanding elastic ball.

In this way the newly-discovered great velocities of the nebulae found a natural explanation or, rather, a more profound background, as an effect of the qualities of space. Eddington extended this theory in 1931 and connected it with the atomic structure of matter in such a way that he was able by mere theory to compute the total number of electrons and protons in the universe (each 1.3×10^{79}), their total mass (1.08×10^{22} solar masses), and the velocity of the nebulae (528 km./sec. per million parsec) out of the known physical constants. The intricate difficulties inherent in the idea of an expanding universe repeatedly raised the question of whether the red-shift in the spectra of the remote nebulae could not be due to other influences working upon the light rays on their journeys of hundreds of millions of years. Milne, in a number of studies since 1932, has developed a different cosmological theory, in which our freedom to choose the measure of time when extrapolating from the present to an ever more remote past is used to construct a simple structure of space. The observed red-shift then means that in the ever more remote past the atomic vibrations took place ever more slowly, if expressed in the time of Newtonian dynamics.

Thus astronomy faces a host of new problems. Problems not as before purely astronomical, but problems of space and time, of universe and science, involving physics, mathematics and astronomy. Problems of what formerly, in the absence of definite notions, was simply called the 'infinite' and now is found to be the many-sided enigmatic object of a new science, a combination of astronomy, physics, mathematics and epistemology, for which the name 'cosmology' has come into use. Problems to be treated by the most acute theorists, handling the newest discoveries of astronomy, the most fundamental physical ideas, the most abstract mathematical methods, under careful reflection as to the basis of all thinking and knowledge. In this fusion with other disciplines, astronomy, the science of the stars, has been transformed into a science of the universe.

CHAPTER 43

THE LIFE OF THE STARS

It was mentioned in Chapter 6 that the Babylonian astronomers, in their instructions for computation, denoted the daily displacement of sun and moon by a term signifying the 'life' of the luminary. Proper motion for them was the characteristic of life. To modern science, life of living beings consists in the first place in transformations of energy. The life-processes of every organism form a part of the great cycle of transformations of matter and energy in nature; every activity or life-phenomenon is an interchange of energy with the surrounding world. The source of all—or nearly all—energy circulating on earth is the solar radiation. All the life-processes in the organisms are a weakened effect of the strong radiation which the earth receives from the sun. And the latter is the effect, 50,000 times weakened by great distance, of the stream of energy pouring out from the sun's surface layers which consist of glowing matter at 6,000°. So, metaphorically speaking, we may say that our life is the remotest gentle rippling of the life, i.e. of the energy transformations, in the sun and, generally, in the stars.

If, therefore, we inquire about the source of all life in the universe, our own life included, we inquire about the origin of the energy of the stars. We faced this problem when we dealt with the constancy of solar heat. The answer given there was not satisfactory; the 20 million years allotted to the sun by the contraction theory was far too short for all the geological processes of disintegration, silt deposit, and rock formation, for which geologists claimed some hundred millions of years. The physics and astronomy of the time, however, could not present a more satisfactory answer.

The problem was presented again, but this time with more detailed precision, when Eddington in 1916 started his researches on the internal constitution of the stars. The mathematical equations determining the internal structure expressed the fact that, in a state of equilibrium, the energy radiated outward by a spherical layer of the star must be equal to the energy produced in the deeper layers. The energy produced in the stellar interior was a fundamental datum in the problem; we had to know where it was produced, by what matter and under what conditions. Strictly speaking, nothing was known about it; so Eddington performed his calculations, using two extreme suppositions: uniform production of energy throughout the entire mass, and production by a 'point source' in the centre only, where the highest temperature and pressure prevail. Happily, the two results did not differ greatly.

Could a source be indicated for the newly-generated energy? This was now possible as a result of the revolution brought about by Einstein in the fundamental ideas of physics. The principle of relativity involves the fact that mass and energy are identical; 1 gm. of mass is equivalent to 9×10^{20} ergs. The immensity of this quantity is evident when we consider that the energy produced by common burning (combining 1 gr. of carbon and oxygen) is only $\frac{1}{10000000000}$ part of it. The production of new energy, then, must take place by the annihilation of mass; in radiating, the star gradually decreases in mass; its matter is 'burning up', as we might call it, in a far more absolute sense than in what is commonly called 'burning'. Eddington, in his classic book of 1926 on the internal constitution of the stars, could put forward two suppositions only; either direct annihilation of matter by the coalescence and mutual destruction of a positive proton and a negative electron, so that the charges disappear and the mass is transformed into high-frequency radiation (gamma rays); or, in another way, by transformation of hydrogen into helium. When four hydrogen nuclei and two electrons combine into a helium nucleus, 0.0124 is lost in mass, i.e., $\frac{1}{320}$ of the combined weight, and is transformed into energy. To compensate for the yearly radiation of the sun (30 million ergs per gramme), the transformation into helium of a quantity of hydrogen is needed equal to one hundred thousand millionth part ($1 : 10^{11}$) of the sun's mass. The resulting lifetime of the sun is sufficient. The question is whether this process actually takes place or, rather, under what conditions it will take place.

Astronomy, to find an answer, had to seek assistance from physics, especially from the new, rapidly-developing nuclear physics. Since in 1919 Rutherford had transformed an atomic nucleus into another atomic nucleus through the impact of extremely rapid particles penetrating into it, many physicists had used this method. Thus detailed knowledge was acquired of all these transmutations, their energy balance and their frequency. The great velocity of the particles (electrons, protons, or alpha-particles) needed to break into an atomic nucleus is found in nature only in the case of extremely high temperatures, of millions and hundreds of millions of degrees. Such temperatures may be expected only in the interior of the stars. The stars are the big world furnaces, which, fed by the energy produced in these transmutations, keep themselves in the state of the intense heat needed.

Thus with the interior of the atoms, the interior of the stars is opening

up before the eyes of the scientists. At the outer surface of a star, with temperatures of about 10,000°, we see exhibited in the stellar spectra the outer electrons jumping up and down or torn away from the atom and recaptured, in an unceasing play of absorption and emission of radiation, accompanying the processes of excitation, ionization and recombination. Deeper in the star in the layers whose radiation does not penetrate to the outside, with temperatures of hundreds of thousands of degrees, entire shells of electrons are torn away from the atoms. Only the more strongly bound electrons, nearer to the nucleus, by being alternatingly freed and captured, transport the energy in alternating absorption and radiation. We may call it the 'internal life' of the star, but this life is passive only, a passing-over of the energy from the interior of the star to the outer layers. At last, when in still greater depth we meet with temperatures of millions of degrees, we find these atoms entirely crushed, as naked nuclei unable to hold the disorderly running host of free electrons and to organize them into stable systems.

But this is not all. At still higher temperatures and velocities, within the densest central parts of the star, new processes come forth, now in the atomic nuclei. Some of those most rapidly running particles, protons or alpha-particles, break into the heavier nuclei to form new ones. Mostly these soon disintegrate by ejecting negative or positive electrons or by dividing, thereby emitting or absorbing gamma-radiation. Some of the nuclei thus formed will be stable, and in this way nuclei of heavier atoms are gradually built up. All these processes, which, owing to the progress of experimental physical data, can now be treated theoretically, with their energy balance and their frequency dependent on temperature and density, constitute the true active life of the stars. It is a continuous play of transformation, of constitution and of demolition of nuclei under extreme conditions of velocity, temperature and pressure, for which we have to make use of million-numbers just as when dealing with the dimensions of the universe. There remained the difficulty that the central temperatures in the stars were found to be insufficient for these processes. It was solved by Gamow, who, by means of wave mechanics, showed that if the velocity of the particles is too small to break into a nucleus, yet a certain petty percentage—sufficient for the effect—manages to creep in.

The science of the nuclear transmutations is as yet in its first stages, but the way is now open towards the solution of the many problems of the origin, life and future of the stars. An investigation by Bethe in 1938 led to the discovery of a cycle of processes of forming and splitting of carbon, nitrogen and oxygen nuclei, which results in building helium nuclei out of protons, to such an amount that it can explain the present radiation of the sun. Thus the old problem of the source of the sun's heat has now at last been solved. Moreover, by knowing the source of the sun's heat, we can derive how it depends on temperature and density and can ascertain that it is produced in the deepest centre of the sun. The obstacle that hampered Eddington in his investigations thus has been removed, and the inner constitution of the stars can be computed with greater exactness.

So we begin to know something of the life-processes in the stars. But life is not only an endless repetition of ever the same transformations of energy. Life is development. Just as in any organism life does not consist solely in the interior processes but also in its growth, in the genesis and development of the individual and the species, so it is in the life of the stars. Life is progressive change. It is a directed process with no return, according to the Second Law of Thermodynamics. Life is ageing, is genesis and perishing.

Here we have the old problem of the evolution of the stars, now appearing in a new context. It is the question of how stars develop and what types and forms transform into what other types. Ever again, when new points of view had been opened through observation in the last century, this question was posed and answered in different ways, in later years in connection with the Hertzsprung-Russell diagram. Certainty, however, was lacking. The life of mankind is too short to perceive continuous changes in the stars; we see the multitude of forms, but how one develops into another, and which forms belong together as older and younger evolutionary phases, can be perceived only by the mind and disclosed by theory. This will be possible when the interior atomic processes are completely known.

Now they begin to be known. We see indeed a progressive change in the processes deep in the interior of the stars. Out of the primary substances—the protons—are built helium nuclei and then heavier nuclei. The hydrogen content of the star gradually decreases; thereby the mean weight of the particles changes, with the result that the density and temperature of the successive layers change. Then also the production of energy changes as well as the spectral type. Bengt Strömgren and Eddington have studied the gradual exhaustion of hydrogen atoms as the determining factor in the evolution of the stars. As far as we can see, the star must finally be extinguished when the stock of hydrogen nuclei runs out. It is possible, of course, that other nuclear processes then play a part and complicate the course of development.

Indeed, the observation of astronomical phenomena shows that everything is not moving along the smooth paths of assured stability. Only from the science of the nuclear processes may we expect the knowledge to explain the lack of stability appearing in the pulsations of the cepheids, and still more to explain the far more serious instability that

appears suddenly in the stellar catastrophes which we see in the flaring-up of novae.

Spectrum analysis, coming into being at the very moment when many bright novae appeared, could establish what happened. In the first flaring-up, which was just caught in some cases, the star showed an ordinary A- or B-type spectrum. After one day it changed into a spectrum with broad emission lines; a layer or shell of hot gases expanded with a velocity sometimes exceeding 1,000 km., clearly flung away by sudden enormous pressure from within. Expanding continually, the shell cooled, so that the radiation and the brightness decreased, and finally it was dissipated. What remained was a small star of the former brightness, but hotter and more condensed, like an O star. We have already found the expanding Crab Nebula in Taurus to be the afterglow of the Chinese guest star, the nova of 1054.

The cause of the instability which results in such sudden flaming-up remains a problem. And even more remarkable phenomena than the ordinary novae have now come to the front. If the seventh-magnitude nova appearing in 1885 in the Andromeda Nebula was really situated within this distant galaxy, it must have had an immense luminosity, 10,000 times greater than the numerous common novae of this system, which reached the sixteenth and seventeenth magnitude only. Such a star of absolute magnitude −15, when situated at the distance of our nearest stars, would be far brighter than the full moon! Baade and Zwicky, in California, in 1934 put forward the theory that such 'supernovae' really occur, whose brightness is not much less than the brightness of the entire galactic system to which they belong. By systematic search, several cases have been traced of bright novae in small spiral nebulae. They are, of course, far less frequent than ordinary novae; the estimate is one every 500 years in every galactic system. Baade and Zwicky think that, in view of its long visibility and slow decline, Tycho's star must have been a supernova, as well as the Chinese nova of 1054. As yet, the supernovae present to the astrophysicists a number of difficult problems.

We now return to the nuclear processes in the common stars. Production of energy in their interior is linked with transmutations of atomic nuclei, producing heavier stable nuclei also. Thus in the hands of the scientists the problem has broadened. The question was: What is the source of the continuously flowing stream of energy pouring out from the stars? The answer now obtained deals not only with the origin of their energy but also with their own origin. This question was raised now and then: What is the origin of all those different atoms, light and heavy, in a determinate proportion found everywhere, on earth, in meteors and in the stars? The idea now lies near at hand that all the present stable atoms have been formed in long periods of development out of the original bulk of protons, the remainder of which appears in the spectra of the A-type stars, the prominences on the sun, and the water on earth, the basic matter of all organisms, including ourselves—without water, no protoplasm and no life would have been possible. This means that in those cosmic furnaces—the central parts deep in the stars—the entire world was, and still is, fabricated, the materials constituting its matter as well as the radiations constituting its life. It is this life which appears, greatly weakened, at the hot stellar surfaces and, again a thousand times weakened, transformed into the life-energy of living beings.

Another difficulty arises: to penetrate into the heavier nuclei, hence to build the heavier atoms, theory may demand still greater densities and greater velocities of the protons, corresponding to still higher temperatures of hundreds or thousands of millions of degrees; these we do not find even in the stellar interiors. Can the heaviest nuclei, of uranium, of lead, of gold, perhaps have been present as original matter in the world? What, then, does the word 'original' mean here? Or shall we assume that the required conditions once existed in the past and now have disappeared—so that the heavy atoms are remainders, a kind of archaeological remains from conditions long passed? It may be plausible to connect the needed high temperatures with the original condition of closely packed galaxies and stars 2,000 million years ago. But all such ideas are a hesitant groping in a dark past.

So here, too, is an endless field of new problems to be cleared, where only the first sods have been cut. Here also we are working with millions, not for distances now and dimensions, but for intensities of energy. Here our path leads not towards the infinitely large, to study the great structure of the universe, but towards the infinitely small, to study the finest structure of nature, of what in the coarse-grained world of the senses is called 'matter' and 'radiation'.

And again this must be accomplished by a combination of sciences, of theoretical physics and abstract mathematics, tested by observation of matter and the radiation of various celestial bodies. Here, too, astronomy takes part in the elucidation of the essence of the world.

APPENDIX A

ARISTARCHUS' DERIVATION OF THE SUN'S DISTANCE

Aristarchus' seventh proposition is the most important, since it is there that the essential numerical result is derived. The demonstration is interesting enough, in its value to future astronomy, to reproduce it here in brief. In the figure A represents the position of the sun, B of the earth, C of the moon when seen halved. Hence angle EBD=angle BAC=3°. Let the angle FBE(=45°) be bisected by BG. Since the ratio of a great and a small tangent to a circle is greater than the ratio of the underlying arcs and angles, the ratio GE to HE will be greater than the ratio of $\frac{1}{4}$ to $\frac{1}{30}$ of a right angle; *i.e.* greater than 15/2. Furthermore FG : GE=BF : BE=$\sqrt{2}$, greater than 7/5; hence FE/GE is greater than 12/5. Combining it with the first inequality, we find the ratio of FE to HE greater than 15/2×12/5=18; and the ratio AB/BC which is equal to BH/HE, hence a little bit larger than BE/HE is certainly also greater than 18. Applying, on the other hand, the proposition that the ratio of a great and a small chord is smaller than the ratio of the subtended arcs, upon DE subtending 6° in the half-circle BDE, and the side of a regular hexagon, equal to the radius, subtending an arc of 60°, we find the ratio of $\frac{1}{2}$ BE to DE smaller than 10, hence the ratio of AB to BC smaller than 20.

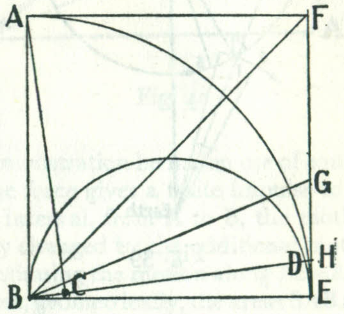


Fig. 38