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ASTRONOMY

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ASTRONOMY

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INTRODUCTION

SINCE this book was first written in 1911 its subject has grown immensely. The Universe of which we now know something is ten thousand times greater in diameter than we supposed 25 years ago. The spiral nebulæ, numbered by the million instead of by the thousand, are each, we believe, a galaxy like our own. Less than a quarter of a century has seen a development of the Relativity Theory, so beautiful a piece of mathematics, so incomprehensible in its demand that we should make no distinction between space and an unreal kind of time, yet with a strange success in explaining certain hard facts.

The words Astronomical Figures have become proverbial, and a satirist has remarked that the magnitude of the lie is inartistic. In a small book like the present we may do well to make sparing use of figures, for several reasons. It is perplexing to change one's unit of distance, but difficult to choose a unit suitable for so vast a range of numbers. The numbers are apt to change rather quickly when we are dealing with the greater dimensions of the universe, and

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require continual revision as methods come and go; and at present no one pretends that they are more than indications of the order of magnitude now becoming known to us. Finally, these astronomical figures convey scarcely any idea to the mind, while they greatly impede the narrative; they will be used as sparingly as circumstances allow.

It has been necessary to rewrite a large part of the book, and to make important corrections where it was not necessary to rewrite. I have thought it better, however, to treat it as a book under revision rather than attempt a completely new work, because there is a certain advantage in referring back to the statements of 1911, and comparing our knowledge then with what we know in the latter days of 1935. The comparison shows more vividly how fast and how far we have advanced. It has not been possible in so small a space to cover all the ground, or even to maintain a strict proportion. There has been no room for references to authorities; an occasional name gives life to the narrative, but I have made no attempt to assess the relative importance of different names, institutions, or nationalities. The overwhelming part played in recent years by the Mount Wilson Observatory has inevitably tended to put in the shade astronomers and observatories doing essential but less spectacular work. And while the obser-

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vations have been made so largely at Mount Wilson, the theorizing has been done more in Europe, and not least in our own country; but it is harder in an elementary book to do justice to the profound thinker than to applaud the highly skilled and ingenious performer.

When the book was first published, I was gently derided for writing a book on astronomy with no illustrations, with no plates, and only one figure in the text. The small size and the low price made plates impossible, and I still have only one figure, but a different one.

A. R. H.

1935 *October*.

CHAPTER I

ASTRONOMERS AND OBSERVATORIES

HOWEVER tempting it may be to inquire what knowledge of astronomy existed among the ancient peoples of the world, how it comes about that some of their buildings are built astronomically, or why it was that their considerable skill in the science was so nearly lost to future generations—we must refuse to be drawn into the charming but devious paths which lead through these parts of our subject. The Chaldæan shepherd had a far better knowledge of the stars and their movements than the modern educated dweller in a glaringly lit town, with a cloudy and smoky sky; he had a traditional lore of the stars which enabled him to regulate his husbandry and to find his way; and his religion, his legends, and perhaps some of his early history can be traced in the names which he gave to the groups of stars which were familiar to him.

The very natural association of religious ideas with the heavenly bodies led to the building of

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temples with a definite astronomical significance, which we can trace in the Temple of the Sun at Luxor, in Stonehenge, and in some other buildings of antiquity. Let us be careful, however, not to go too far in finding an astronomical meaning for every line and for every angle in such a building; not to ascribe to the builders of old a knowledge and an accuracy which the facts do not warrant; and not to pretend by measurement and calculation to arrive at the date of the building with all the authority which should attach to the solution of an astronomical problem.

It must appear curious at first sight to any reader of the history of astronomy, that while many of the principal facts, the rotundity of the earth, the gradual change in the position of the pole among the stars, were known to the famous astronomers of antiquity, who were Greeks, yet the authority of the Greek philosopher Aristotle was in the beginnings of modern science used to stifle inquiry into the truths of astronomy. Planets must move in circles because the circle is the only "perfect" figure. Seven is a perfect number, and therefore if you have found seven of a thing you need not waste time looking for an eighth. This was the kind of argument that passed for scientific in the Middle Ages; this was the kind of prejudice which the early European astronomers had to rid their own minds of first,

TYCHO BRAHE

and then to banish from the minds of others. It could be done in only one way, by insisting on first observing what actually happened and then constructing arguments to fit the facts.

Foremost among the men who insisted upon observation and experiment was the Danish nobleman Tycho Brahe, who was above all things an experimenter. On the little island of Hven, lying off Elsinore in the Sound between Denmark and Sweden, Tycho built a magnificent observatory, and fitted it with splendid instruments all of his own design and make. He founded in fact the modern science of observational astronomy. In the Royal Library at Copenhagen one may see the great journals of observations which Tycho and his assistants made for some twenty years in that island—catalogues of stars, places of the planets and of the moon, places of comets, and all the regular routine of a modern observatory. There are two things to be remembered about Tycho's work; it was immensely more accurate observation than had ever been made before, and it was done before the telescope was invented.

One is so accustomed to think of an astronomer at the eye end of a telescope, that it seems extraordinary he could do much without one. True, Tycho was limited to the stars and the planets which the unaided eye can show, but there was much to be done with these which had

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never yet been done. Instruments mounted on pillars, furnished with circles or with portions of circles divided into degrees and parts of degrees, provided with carefully made sights, were capable of considerable accuracy in the hands of a man with a genius for handling instruments. At least they were capable of providing the mass of observations upon which Kepler founded his laws of planetary motion, and upon which in the end Newton rested his demonstration of the principle of universal gravitation.

But a few years after Tycho's death in 1604 the telescope was invented in Holland. There are several claimants to the invention, and their respective merits are somewhat obscure. Nor is it quite certain that posterity has been right in giving to Galileo the undivided credit of first turning the telescope to the skies. His famous discovery of the four satellites of Jupiter led to his immediate recognition of the truth they demonstrated, that the earth and the planets move round the sun, as Copernicus taught. The persecution which he suffered, for teaching his opinions, threw a romance about his life which has obscured the fact that the injustice of others made him unjust himself. A German astronomer, Simon Marius, discovered the satellites of Jupiter within a few hours of and probably before Galileo. He had made many observations of them and constructed a first rough table of

INVENTION OF TELESCOPE

their motions. Galileo roundly accused him of stealing his observations and his credit, and the world, believing Galileo, went on calling Marius an impudent pretender until within the present century.

(The first discoveries of the telescope opened a new heaven to men's eyes. There were mountains in the moon, spots upon the supposed unblemished surface of the sun; the planets became worlds like the earth, and the Milky Way was resolved into innumerable stars. Astronomers of all countries set themselves to improve the telescope, and up to a certain point their progress was excellent; but at that point they stopped. For technical reasons, into which we can hardly enter, those who aspired to make their telescopes more powerful were forced to make them inordinately long; and such instruments, though they were fairly satisfactory for viewing the planets, were very little good on faint objects. Hence we find in the 150 years after the invention of the telescope that little progress was made in exploring among the stars and nebulae. In other directions, however, immense advances had been made.

Newton at Cambridge had made his immortal discovery of the principle of universal gravitation; Halley in London had spurred him on to complete his work and publish it. On the continent of Europe mathematicians had opened

ASTRONOMERS AND OBSERVATORIES

up regions of mathematical analysis, in which Newton's principle was the foundation, though his methods were superseded by others more tractable in ordinary hands.

The biography of Newton by Professor L. D. Moore, published in 1934, displays rather than explains Newton's curious distaste for the exercise of the powers which made his name immortal. Being Lucasian Professor in the University, he had to lecture, and by the conditions of his office at that time had to deposit with the Vice-Chancellor for preservation in the University Library the manuscripts of his lectures which he delivered once a week during one term in the year. The set entitled *De motu corporum* shows that he gave his pupils one or two propositions in each lecture, and went on from year to year with fresh propositions, which must have been very discouraging to the pupils of successive years. It would seem that having to deal with the subject he dealt with it, but was very little interested in imparting it to others or publishing it to the world; and he was always more than ready to turn from astronomy, in which his insight was super-human, to alchemy and the interpretations of prophecy, in which he made little mark. When he had left Cambridge for London his mathematical powers did not decay, for on the celebrated occasion when Leibnitz challenged the mathematicians of the world to

ISAAC NEWTON

produce the solution to a problem within a year, Newton solved it after dinner on the day on which he received it. But otherwise he simply took no interest in mathematics any more.

The doctrine of Copernicus that the earth is a planet and moves round the sun with the others was so plausible, and explained things so well, that it was gradually accepted long before it was proved by demonstration. In the seventeenth century it was no longer impious to believe it, and like Fontenelle's Countess, people had "become accustomed to it and slept as well as Copernicus himself." But from time to time further attempts were made to actually prove the motion. The ingenious Robert Hooke erected a zenith tube in Gresham College, made some observations founded upon the most correct principles, but never pursued to the end. He was satisfied by finding movement in the star, Gamma Draconis, without perceiving that it moved in the opposite direction to that which would support his theory. It was not till many years later that Bradley, following the path with more diligence, discovered the aberration of light which proved the motion of the earth in an unexpected way, and with his later discovery of the nutation of the earth's axis, reduced to order all the questions connected with the accurate determination of star places

ASTRONOMERS AND OBSERVATORIES

in the sky. The foundations of the astronomy which concerns itself with minute nicety of observation, with profound depths of calculation, had been well and truly laid. Upon that foundation generation after generation of mathematicians and of observers have built; with hardly any pause the edifice of precise astronomy has arisen, stone by stone, till to-day it forms the immense structure into which it is hard to enter without the master key of some mathematics and a great deal of technical knowledge. All this side of astronomy lies outside the range of a small book like the present. We shall make some acquaintance with its results in the chapters which follow; with its methods and with its technique we cannot concern ourselves further.

Upon the other side of astronomy lies the realm of exploration and discovery, whose frontiers receive a great extension with every considerable advance in instrument building or new method of observation. Such an extension was made by Sir William Herschel. The reflecting telescope which Newton had invented made at first slow progress in size or in use. It remained an interesting example of optics rather than an instrument of any practical importance, until Herschel found himself at last in the position to carry out his cherished scheme. What it was that implanted in Herschel's brain

WILLIAM HERSCHEL

the resolution to explore the sky is of course unknown. All that we do know is that during years of hard work as a teacher and conductor and composer of music he steadily kept in sight the purpose, that he would make greater telescopes than any which had yet been made, and that he would thoroughly search the heavens. It was natural that his thoughts should turn to the reflecting telescope, whose construction, though tedious and delicate, is yet relatively simple and within the power of a skilled amateur—as has often been proved since Herschel's time. Of the way in which Herschel made his telescopes there is no sufficient account. The observations which he made with them are the foundation of what we know to-day about the nebulæ and star clusters.

The first half of the nineteenth century was again a period of steady rather than of startling progress. Bessel in Germany, Airy in England, systematized and organized observatory work so that the methods of to-day bear the indelible stamp of their talent. Adams in England and Leverrier in France discovered Neptune by calculation—a feat which produced an impression more profound than any other event in the history of science. In Ireland Lord Rosse made in his own workshops the gigantic 6-foot mirror which remained until lately unsurpassed in sheer size. Then just after the middle of the

ASTRONOMERS AND OBSERVATORIES

century came the invention of spectrum analysis by Kirchoff, and its application to the stars and nebulæ by Huggins.

This discovery marks an epoch as distinctive as, perhaps more distinctive than, the discovery of the telescope, for it gave to astronomers a new sense. The telescope is but an eye allowing man to see farther and better than he could see before. The spectroscope enables him to achieve what might have seemed perfectly hopeless, to determine what the stars are made of by analysing the light which they send us; and to determine the speed with which they are approaching or receding in the line of sight.

With this new sense at its command astronomy made at once a brilliant advance into regions which had been closed to all examination. It was immediately clear that the stars are suns like our sun, while many of the nebulæ are but clouds and drifts of shining gas. It was at once possible to prove that the substances, common or rare, which are found in the crust of the earth are present as glowing vapours in the distant stars, and that from end to end of space matter is essentially the same. Some light rays there were, indeed, in the nebulæ or in the stars which were not at once run to earth. But the stars have become laboratories in which the elements can be studied in conditions beyond the range of terrestrial experiment.

CELESTIAL PHOTOGRAPHY

The application of photography to astronomy followed hard upon the introduction of light analysis. But for all except the brightest objects the necessary exposures were so long that a wet collodion plate could not deal with them; the plate dried during the exposure and lost its sensitiveness. Real facility in astronomical photography came with the introduction of the dry gelatine plate about 1880.

The real advantages of the photographic plate lie in its power of storing up impressions by long exposure until they become developable; its power of recording simultaneously a number of things which could be observed only one by one; and its power of taking in a very much larger field of view than can be seen at one time in the visual telescope. The first and the last are responsible for the great success with which the star camera portrays star clouds and very extensive nebulæ, which cannot produce their proper effect when they are seen piecemeal. The second and the last have revolutionized many branches of precise astronomy by transferring the work of measurement from the micrometer on the telescope to the measuring machine in which the negative is placed. This has great advantages; among them are two which can be appreciated at once. It economizes time, because one can take advantage of an hour of clear and steady sky to take a photo-

ASTRONOMERS AND OBSERVATORIES

graph which will provide work for a week of cloudy weather. And secondly—a more technical reason—it greatly facilitates the troublesome corrections which have to be applied to the measures, because they can be calculated and applied all at once, instead of one by one.

The requirements of photography have made new and very interesting demands upon the skill of the optician and the mechanic. The optician is called upon to design lenses which shall give the greatest concentration of light for photographing faint objects, and the best possible definition over a large field of view for photographing extensive objects like the star clouds of the Milky Way; or to grind and polish immense parabolic mirrors and mount them so that they shall not bend or shift as the telescope is moved, or alter their shape with temperature changes.

The mechanic is required to make long telescopes without flexure, and to make driving clockwork that shall cause the telescope to follow the daily motion of the stars without allowing them to wander upon the photographic plate.

With every increase of size in astronomical instruments the question is asked, Has the limit of successful construction now been reached? Is it possible or profitable to go farther? Such questions cannot receive any positive answer,

REFRACTING TELESCOPE

but it may be worth while to inquire for a moment what prospect there may be of providing the astronomer with greatly increased telescopic power.

The greatest object glass which has been successful is that mounted at the Yerkes Observatory of the University of Chicago. Its diameter is 40 inches; its focal length is 62 feet; and it requires for its installation a dome only two or three feet smaller than the inner dome of St. Paul's in London. It has been in existence some forty years, and it remains the largest lens at work. What has put a stop to the series of larger and larger glasses which was made during the last thirty years of last century? There are several reasons;

The first of course is the expense. The cost of mounting one of these big refracting telescopes is immense. The telescope itself increases in cost at a rate out of all proportion to its aperture; the building in which it is housed, the revolving dome and the rising floor, soon come to cost more than the telescope. Hence there has arrived a time when the increased cost of installation is out of proportion to the gain in light.

A second reason against attempting to build larger refractors is the extraordinary difficulty in getting large discs of optical glass. The optician could handle a bigger disc than the glass-maker can supply. The difficulty lies, of

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course, in getting the disc of glass uniform throughout; a patch of density slightly greater than the rest will ruin it, unless the excess can be removed by reannealing—a process which occasionally succeeds in a remarkable way, which is very curious when one considers that the glass is not, in its last stages, ever raised to anything like melting-point.

No great refracting telescope has been completed for many years, and it seems unlikely that any will be built in future. In the 40-inch at Yerkes they reached the limit of profitable construction, and it is doubtful if to-day any glass-makers would undertake confidently to make discs of optical glass nearly as big as 40 inches. If the art has fallen into abeyance it is partly because it was always highly personal, but more because the ambitious glass-founder has devoted himself to a different problem, making great mirrors.

In 1911 we could write that Lord Rosse's 6-foot mirror of the mid-nineteenth century remained unsurpassed in sheer size; the 60-inch at Mount Wilson was at work; the 100-inch only projected. Many of the results in the present book are due to the completion of the 100-inch, which has a worthy rival in the 72-inch at Victoria, B.C. A mirror one inch bigger has been mounted at Toronto; another of the same size is contemplated when the Radcliffe Obser-

REFLECTING TELESCOPE

vatory at Oxford moves to Pretoria; and several others not quite so big. If this book ever attains another revision, we shall doubtless have to describe surprising results obtained with the 200-inch mirror which is now being made, not without trouble, for a new observatory of the Carnegie Institution, daughter to that at Mount Wilson.

A device which will have great importance for the reflecting telescope is the method of depositing on glass, by an electric discharge in high vacuum, beautiful films of metals, particularly of aluminium, with a splendid polish and singularly immune to atmospheric corrosion. To have a reflector which will stand being dewed and retain its polish for months if not years, and what is more, reflect ultra-violet light, is an agreeable prospect for the future; only the technical difficulty of a large vacuum chamber prevents its general use at the moment.

Whether for direct photography, or for spectrography, the need is ever for more light-gathering power, and the reflecting telescope with its short focal length gains more effectively than by its mere aperture. On an extended nebula, the speed depends upon the ratio of the aperture to the focal length, the size of the image upon the focal length alone. For images of individual stars the law is more complicated in theory, but in practice much the same, since

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unsteady seeing enlarges the smallest images much beyond their theoretical size. The same unsteadiness wastes light in spectrography because the star jumps off the slit of the spectrograph; so that the tendency nowadays is to concentrate upon the greatest possible aperture, and a focal length not more than five times as much, which implies the reflecting telescope. The great refractors which survive from a former age are barred from sharing now in sensational work, but retain their particular rôle in the discovery of ever more double stars and in making large-scale photographs for precise measurement.

But the field of view of the reflecting telescope is limited to about 20 minutes of arc; beyond that the images fall off very rapidly, and star charting demands, and now obtains, star cameras with quadruple or complex objectives which cover 15 or 20 degrees.

While the photographic telescope has been getting larger, the fundamental meridian-circle tends to be smaller, because it has no longer the ambition to deal with faint stars, which are taken care of by the star cameras just mentioned. The ingenuity of instrument-makers has been directed rather to improving the mountings and the building in which they are installed; to making the instrument stand as nearly as possible effectively in the open air;

TIME

and to eliminating the obscure systematic effects of temperature gradients, both in the air and in the foundations. The first result of wireless intercommunication of time was to show the astronomers at the National Observatories that their time was not as accurate as they had thought, and it is still unexplained why the time of Washington, for example, should agree with Greenwich for a couple of months and then wander away by as much as $\frac{1}{10}$ th of a second. One fact has emerged quite clearly, that the big instrument does not give such accurate times as the small one, and the best time-observation is now done by instruments of about 4 inches in aperture which can be reversed in the course of the observation: a drastic way of eliminating instrumental errors which is impossible with larger instruments. The vagaries of an Observatory's time have thus been diminished but still persist, and it is sometimes asked whether the cause does not lie in some fluctuation in the direction of gravity to which the instrument is levelled. That, if it were proved, would be a serious blow to progress in accurate time-keeping; it may seem a fantastic idea, but not more fantastic than the fairly proved change in the rotation of the earth three times in the last century and a half.

The most striking improvement in the equipment of precise astronomy has been not in the

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meridian circle but in the clock. Many years ago it was understood that if one could not realize the ideal, of a pendulum perfectly free, because the pendulum had to be engaged at some part of its swing in receiving an impulse to keep it swinging, and in sending a message to tell what time it was keeping, then the next best thing was to limit this engagement of the pendulum to as short a period as possible at the precise middle of its swing. But to state the principle and to put it into practice are two very different things. The problem was some twelve years ago solved not by a clock-maker but by a railway engineer—Mr. Shortt of Exeter—in conjunction with Mr. Hope-Jones of the Synchronome Company, and the Shortt clock is now recognized as so far superior to any other that it is an essential instrument of any well-equipped observatory. An enthusiastic American physicist, Mr. Loomis, has mounted a battery of three and studied them minutely with the quartz-crystal resonator, another new and important development in time mechanism. Scrutinized by an apparatus which will vibrate 100,000 times a second with almost unfailing regularity, the Shortt clocks have been found still not quite perfect: there are some residual irregularities which at present defy explanation; but the battery of three was unanimous in detecting the effect in the change of the value of gravity

CLOCKS

caused by the passage of the moon across the meridian: a disturbance with a total range of about three ten-thousandths of a second.

The Shortt clock is then a very perfect instrument; but it is too early to say that it will some day reveal irregularities in the rotation of the earth, such as were mentioned above. Nothing manufactured, however well annealed, is quite safe from rearrangement of its molecules, nor is it certain that in the last refinement anything like a pendulum-bob is absolutely rigid, with no viscosity.

These magnificent instruments of the great observatories can do things which no other telescopes can do, and it is an immense advance that their constructors have made. There is naturally a danger that the owners of smaller telescopes will be depressed, and will perhaps underestimate the possibilities that they have within their reach if they have courage. There is, as a matter of fact, still plenty of excellent work for the smaller instruments to do—both for the modest observatory and for the still more modest amateur. In various places as we proceed we shall consider what work there is within reach of the amateur observer. For the moment let us return to the public observatory, and glance at its equipment. We shall suppose that it is a University Observatory, well but not

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extravagantly equipped, and prepared for teaching as well as for research.

First there will be a meridian circle—a telescope of moderate aperture, say 6 inches—mounted upon very solid piers so that it will turn from north to south, through the pole and the zenith, pointing always to the meridian of the place. In the focus of this telescope there is a set of wires, equally spaced about a centre wire which forms the visible instrumental meridian. And the telescope is provided with a divided circle which serves to measure how far it is turned from the zenith, north or south. With this instrument a double observation is made—the time at which a star crosses the meridian, and the distance from the zenith at which it passes. The purpose of the instrument is first to find the time, the correction to the clock from observations of known stars; and then to observe the places of stars which are not so well known, for making star catalogues; or to observe the places of the moon and the planets, for improving the theory of their motions. All this kind of work is called astronomy of position, and belongs to the department of meridian observation.

Secondly, there will be the department of the equatorial, a telescope mounted and driven by clockwork so that the effects of the rotation of the earth are annulled. In the equatorial the

EQUATORIAL TELESCOPE

star can be kept in the field of view for as long as may be desired; it does not rush across the field of view and vanish, as it does in the meridian circle. With the equatorial one studies and makes drawings of the planets, measures the relative positions of the components of double stars, or searches for new comets.

Then, more likely than not, there will be another equatorial telescope, with its lens corrected for the photographic instead of for the visual rays of light. Such a telescope is in reality a camera, though different in proportions from the ordinary landscape camera of commerce. The lens will be perhaps 12 inches in diameter; the tube about ten times this diameter in length. There will be no bellows, because the camera is in this case used at a fixed focus, the focus for infinity, and the small range of focusing required to bring the plate into exact adjustment can be provided in other ways; and bellows would be very much out of place in an instrument which requires to be rigid in a high degree. Lastly comes the carrier for the photographic plate, which is perhaps 6 inches square, not nearly so large as the objective. It is this curious proportion between the lens and the plate which makes the photographic telescope look unlike a camera. One is so much accustomed to seeing an inch of objective covering a photographic plate $8\frac{1}{2} \times 6\frac{1}{2}$ inches, that it seems at first sight absurd to

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require 12 inches of objective to cover 6 inches of plate. But we must remember that we want a large objective because we are going to photograph very faint objects; and we use a small plate because we are content only with the centre of the field, where the definition is of the very best.

The photographs taken with this instrument, being intended for accurate measurement, will be on a large scale, with the stars widely separated. The magnificent, densely crowded pictures of the Milky Way, which make a splendid show on the screen at a lecture, or in a work on astronomy which can afford illustrations, are made with an instrument differently proportioned, with a focal length only four and a half or five times the aperture, and with an objective of several lenses, very much like the ordinary high-class camera lens. Then, with an exposure of several hours and a relatively much larger plate, one can concentrate many square degrees of sky into one picture, which looks magnificent, and is very useful for study of the broad features of the sky, but is not good for measurements of precision.

Our observatory will also have a department devoted to astrophysics, that is to say, to the study of stars and nebulae with the spectroscope. One of the equatorials will be equipped with the apparatus of slit, prism, and camera which

SPECTROSCOPE

photographs the result of the light analysis, the spectrum with its bright lines coming from glowing gas, or its dark lines telling of absorption in the stellar atmospheres. When the spectrum is obtained it requires interpretation; the lines in the spectrum, for example, may correspond in position exactly with the lines which are produced by the vapour of iron, but some may be abnormally strong and others almost invisible. It is then the task of the astrophysicist to discover what this difference means. He turns the observatory into a physical laboratory, equipped with dynamos, electric arcs, furnaces, pressure pumps, and vacuum pumps, and he tries to reproduce upon earth the conditions, indicated by the abnormal spectrum, which are present in the stars.

The solar physicist will have quite a different equipment. He has plenty of light available, so that his instruments need not be very great in aperture, and may be very long, to give him pictures upon a large scale. So he will have a very long fixed horizontal telescope and spectroscope, into which the sunlight will be reflected by a slowly rotating mirror, the coelostat. Or if a horizontal telescope is too much affected by the radiation from the heated ground, he will substitute a vertical telescope, with the coelostat and objective mounted on a high tower, and the spectroscope at the bottom of a deep well below.

ASTRONOMERS AND OBSERVATORIES

But he will not be able to do this unless he is very rich.

Lastly, our observatory library will contain the publications of several hundred observatories that publish observations more or less regularly, and journals running to several thousand pages annually, and it is quite impossible for the astronomer to read everything that appears. Hence there has arisen in astronomy, as in other sciences, the need for carefully prepared and arranged abstracts of each year's work, and several volumes are now devoted annually to this purpose. From this mass of raw material the evidence on any point is gradually extracted and worked up into a case; and in the end years of observation, hundreds of pages of publication, months of calculation and discussion, produce the brief conclusion, for example, that the gaseous nebulæ are concentrated upon the Milky Way.

We have referred already to the astronomer's dependence upon the engineer, the optician, and the glass-maker. We must not omit the photographic plate-maker and the ingenious technicians who fashion other tools recently placed in the astronomer's hands, such as the photo-electric cells for measuring a star's radiation; and the electric photometers for measuring the intensities of images on photographic plates. Lastly, a word upon the calcu-

“NAUTICAL ALMANAC”

lating machine. No observatory is complete without a staff, large or small, of computers who perform the rather weary grind of applying all the corrections for refraction and instrumental errors, and take out the effects of the aberration of light and precession, nutation, proper motion and all the other things that make fundamental astronomy so complicated. There are also the smaller establishments in several countries which calculate the fat volumes of figures which we call the *Nautical Almanac*, the French the *Connaissance des Temps*, the Germans the *Berliner Jahrbuch*, and only the Americans accurately an Ephemeris: dull but indispensable publications in which the co-ordinates of the sun and the planets are calculated for every day, the places of the moon for every hour, and the places of some 500 or 600 stars for every ten days: not to speak of satellites, and eclipses, and occultations, all of which are predicted from intricate calculations based upon tables representing the dynamical theory of movements in the Solar System. A revolution has come over the methods of calculating, at least in England; the familiar table of logarithms is banished, and all the calculations are done by machinery: not only the familiar multiplying machine, which multiplies 8 figures by 8 with incredible speed, but vastly more complicated machines that are fed with a certain number of quantities from the

ASTRONOMERS AND OBSERVATORIES

theory and build up detailed tables upon them in a mysterious way, finally typing the results all ready for the printer. Reform is in full swing, and computers in any subject will do well to study the practice of the British Nautical Almanac Office.

In concluding a chapter on Astronomers and Telescopes, we may remark that the application of photography has made a difference which is hardly yet realized. Since photographs can be reproduced and put into the hands of all, it follows that any student of astronomy is the potential possessor of the greatest telescopes in the world. By this we mean that astronomical work of real importance—not merely intellectual recreation, but study which may make valuable contributions to knowledge—can be done upon published photographs.

CHAPTER II

THE SUN AND MOON

THE sun, the overpowering source of light and heat and energy which makes life upon the earth and all our activities possible, and the moon, the dead lifeless companion of the earth, whose most obvious use is to act as a pale reflector of sunlight to mitigate the darkness of our nights, are at opposite ends of the series in which we may arrange the components of our solar system. Nevertheless, we will study them together.

The study of the sun is essentially modern, because it depends very little on the formal laws of geometry, and requires above everything some elementary ideas upon the properties of matter, which are of quite modern growth. Little more than a hundred years ago, for example, it was possible for scientific men to discuss quite gravely, without ridicule, whether or not the sun might be inhabited; not on his surface, indeed, which was undeniably too hot, but perhaps somewhere in the darker layers which we seem to see below

THE SUN AND MOON

the brilliant surface, when we look down into the depths of a sunspot. To-day, such an idea has only to be mentioned to appear ridiculous. We can no longer be content with the plain fact that the surface of the sun is pouring out immense supplies of heat and light; we ask ourselves at once, whence come those supplies; we realize that they must be brought up to the surface from within; and we see that it must be even hotter inside than it is on the surface. There is no more a question of cool, habitable depths below. Nor is it probable that the sun is anywhere solid, in the ordinary sense of the term.

With a diameter one hundred times that of the earth, the average density of the sun is no more than a quarter the average density of the earth, and not more than one-half the density of the earth's rocky surface layers. One can account for this combination of great size and little density only by supposing that the sun is in a state of what must be called gas, since it is neither solid nor liquid, but which is gas in a state which we cannot reproduce experimentally, a kind of thick treacly fluid, denser than water, yet with the elastic properties of a gas. Between the interior and the surface there must be a continual rush of hot currents bringing up from inside the heat which is poured out at the surface.

SUN'S ENERGY

But how is the supply below maintained? The sun is not burning, in the sense in which a coal fire is burning and producing heat by combustion in the oxygen of the air. The way in which a gaseous body may radiate heat, and yet remain hot or even become hotter, was explained by Helmholtz in a simple manner. When a stone is dropped upon a pavement, it acquires a store of energy during the fall which is suddenly dissipated when the motion is stopped. The energy which it had acquired in falling is converted into heat, which is radiated away. But the stoppage need not be sudden. The same amount of heat would be produced if the stoppage were ever so gradual. Suppose then that the sun, under the influence of its own strong gravitation, contracted in diameter a thousand feet. This would supply all the heat which the sun radiates in five years. This principle of Helmholtz is able to explain how the sun's heat might be maintained for a hundred thousand years without any appreciable decrease in his apparent size. During hundreds of thousands, or millions of years, the sun might be pouring out his enormous supply of heat, year by year, and might all the while be actually growing hotter. But we cannot in this way provide for the maintenance of the earth as a planet deriving its heat from the sun, for a

THE SUN AND MOON

period extending into the past more than twenty million years.

There is another source from which the sun might derive heat, by the fall of material upon his surface from what we are accustomed to regard as empty space. This involves a continual increase in the mass of the sun, which would shorten the year, for dynamical reasons. Calculation shows that four thousand million tons of matter might fall on the sun every second, without diminishing the length of the year by more than a thousandth of a second per year. But there is no reason to think that anything like this amount of matter falls into the sun; and if it did, it would not nearly maintain the radiation.

When we became familiar with radium and with all the radio-active substances we learned that atoms of matter contain stores of energy which are ordinarily locked up, but which in certain bodies can gradually escape, and produce heat and many kinds of electrical action. These radio-active bodies exist in the crust of the earth in most minute quantities, yet it has been calculated that the earth would be far hotter than it is, were the interior as rich in radium as are the surface layers, and were the radium able to produce heat in the interior as it can at the surface. In 1911 it appeared that radio-activity might be impor-

SOLAR SURFACE

tant in explaining the maintenance of the sun's heat, for the hundred million years or so then demanded by geologists. But two thousand million years is now reckoned the age of the earth, and it is necessary to believe that in some way mass is annihilated and transformed into radiation. To maintain its supply of heat the sun would lose four million tons a second; but is so big that it can do this for two thousand million years without losing more than about one eight-thousandth of its mass. We shall deal with this matter a little more fully in the chapter on the stars.

It is an interesting question, why does the sun, though it is but a sphere of gas, have a visible and fairly definite surface? The telescope shows that the surface is granular, formed of small bright cloudlets in rapid motion, changing in pattern from minute to minute, so that on photographs taken ten minutes apart it is impossible to identify the individual cloudlets, so rapidly have they moved. In this shining surface, the photosphere, are the rents or vortices from which the cloudlets have been sucked away: the sunspots which were discovered immediately the first telescope was turned upon the sun, and which are still most fascinating objects for study in small telescopes. In spite of the

THE SUN AND MOON

prolonged and minute attention which they have received for many years, and in spite of the refined and ingenious modern processes which are now employed in their examination, their nature remains something of a mystery. They are evidently holes in the photosphere from which the bright cloudlets have been temporarily removed. One may watch the edges of a spot as it were melting away and falling in; one may see, in the spectro-heliograph pictures which we shall presently describe, how the masses of hydrogen and calcium vapours which lie above and around them, are whirled in vortices. The sunspot is both an uprush of heated matter from within and a downrush of cooled gas from without.

Whatever may be the detailed physical structure of sunspots, it is evident that they are an index to an activity which is not merely superficial, but affects the whole structure and functions of the sun. For many years the ever-varying number of spots had been observed and recorded without any suspicion that they were governed by a set of complicated and far-reaching laws. But about the middle of the nineteenth century it was remarked by Schwabe that the number of spots increased and diminished in a period which is roughly eleven years; and very soon afterwards it was found that other phenomena, with no apparent

SUNSPOTS AND MAGNETISM

connection, obeyed the same law. Displays of the aurora are frequent in high latitudes, and most frequent when the number of spots is great. Occasionally the aurora is seen in temperate latitudes, and a remarkable display is generally associated with an outbreak of unusually large spots upon the sun. Again, the magnetic compass is subject to a small daily swing backwards and forwards, which is greater at some times than at others; the amount of the daily swing is closely associated with the number of sunspots, and upon some days when sunspots are unusually active we have what is called a magnetic storm, when the compass needle is violently disturbed and telegraphic communication is interrupted by currents of electricity in the earth.

These widespread effects can hardly be ascribed directly to the spots upon the sun's surface. Rather should we consider that all three, sunspots, auroræ and magnetic disturbances, are manifestations of some deep-lying cause in the sun, of whose nature we are at present ignorant. The whole phenomenon is indeed extremely complicated. At the beginning of each new period the spots break out in middle latitudes upon the sun. They break out rather suddenly, and in a year or two the number and area of the spots becomes a maximum. Then they gradually decline,

THE SUN AND MOON

and, as they do so, they approach more and more nearly to the sun's equator. Their period of eleven years is far from regular. At different latitudes they cross the sun's disc in different times, making it appear that the sun does not rotate as a whole. At one time a great sunspot will be associated with auroræ and magnetic storms; another equally great will not; and sometimes one will have the disturbances upon earth without a visible disturbance on the sun, in which case it is of course permissible to suppose that the spot is on the far side of the sun.

Above the photosphere of the sun lie the regions which become visible to the eye only when, at a total eclipse, the moon intervenes exactly between the sun and the earth. So nearly of the same apparent diameter are the sun and moon that it depends upon the position of earth and moon in their not quite circular orbits, whether she shall appear at the moment of eclipse slightly larger or slightly smaller than the sun. If she is smaller the eclipse is annular, that is to say, a narrow ring of the sun is visible all around the moon, and the phenomenon is of no particular importance. But if the moon happens to be in a part of her orbit nearer the earth, and the sun looks a little smaller than the moon, then as the last segment of the sun's photosphere is covered by the

SOLAR ECLIPSES

moon, there appears a narrow belt of bright crimson with prominences rising from it, and the most beautiful halo of pale white light, which is the sun's corona.

It is great good fortune that we can see the corona at all. Were the moon ten per cent. less in diameter eclipses would always be annular, and we should be unaware to this day of the very existence of the sun's most beautiful member. As it is, the moon is just large enough, when circumstances are favourable, to cast a narrow shadow, perhaps seventy or eighty miles across, on the earth.

It is the object of eclipse observers to get within this shadow, and with a battery of instruments to make the most of the precious few minutes while the shadow is sweeping across them ; the nearer they are to the central line, the longer does the shadow take to cross them ; but in no case can the duration of total eclipse exceed about seven minutes, and the average is more nearly three or four. The path of an eclipse passes indiscriminately over land and sea, habitable country and desert; so that eclipse observers find plenty of variety in their journeys, and travel to out-of-the-way places.

There are few quests of a more sporting nature than the pursuit of the solar corona. An eclipse expedition involves months of pre-

THE SUN AND MOON

paration at home; the construction and testing of special instruments; the building of portable huts and the provision of all kinds of stores both scientific and domestic; then the long voyage and sometimes the perilous landing in the surf of a coral island; the anxious weeks of building the observing-huts and setting up the instruments; the long practice and drills, so that each member of the party may do exactly the right thing at the right instant in operating a battery of cameras and spectroscopes during the precious seconds of totality. Then if the sky has been clear comes the anxious, trying work of developing photographs in a temporary darkroom, with the air much too dusty or water much too hot and dirty to make photography easy. And finally, after a safe return home, there are more months to be spent in measuring and discussing the photographs obtained, and in publishing the new conclusions which result from their study.

The writer's personal experience has been confined to two eclipses, both completely cloudy; and a cloudy eclipse does show one part of the phenomenon particularly well—the shadow which comes sweeping across the country at twenty miles a minute. From the hill above Vadsö on the Varanger Fjord in 1896, one had a long view up the fjord

ECLIPSE EXPEDITIONS

to the west. The party had left their ship at midnight in the rain; the eclipse was to be at five in the morning, and in those high latitudes in August the sun scarcely set. Breaks in the cloud at intervals gave rise to hopes which were as quickly dashed. For a few moments during the partial phase of the eclipse the sun came out; then the clouds settled down and took on a gloomy purple as the light failed and totality approached. Then the shadow, plainly visible upon the sea, came tearing down the fjord from the west. In 1927, for the first time for about 200 years, an eclipse track crossed northern England, and most of us had a similar early morning experience.

An astronomer plays for high stakes when he devotes the best part of a year and a good deal of money, not always his own, to an enterprise whose success depends absolutely on clear sky at the critical moment. When he wins, the stakes are worth having. He no longer occupies himself with the prominences, for he has found a way of observing them without an eclipse. But practically all that we know of the corona has been gathered in the couple of hours obtained by adding up the scattered minutes of totality, during the eighty years or so in which eclipses have been seriously observed. The main facts about the corona

THE SUN AND MOON

are relatively simple. Its light is largely scattered sunlight; but there is also present a gas which emits a green line not yet identified as belonging to any known element. Its structure depends upon the sunspots. When the spots are many the corona is condensed, with short rays somewhat evenly distributed. When the spots are few the corona has long curving extensions like wings in the plane of the sun's equator, with a brush-like structure of short rays proceeding from the poles. The form of the corona is, then, one of the inter-related effects of that prime cause, whatever it may be, which is responsible for the sunspot, the aurora, and the magnetic storm. How the effect is produced remains nearly as much a mystery as it was when the corona was first photographed.

Apart from these complicated questions the corona has an interest all its own as the most splendid feature of a rare and intensely impressive event. So long as the slightest segment of sun remains, no corona is to be seen; nothing is ever seen of it in the narrowest annular eclipse. So long as even a single bead of bright light on the moon's limb marks where the sun is still shining through the notch of a lunar valley, the corona remains invisible; as the moment of complete totality arrives it flashes out clear and pale on a deep blue or purple

SOLAR PROMINENCES

sky; and it vanishes again at the first instant of returning sunlight.

Before the eclipse of 1868 the solar prominences were visible only during totality, but since then have been visible on any day to anyone who can follow the path which Lockyer and Janssen indicated. The prominences are eruptions of glowing hydrogen, which are thrown up from the sun's surface, and appear during eclipses as the red tongues of flame round the dark edge of the moon. Since they are gas, they emit rays of a few definite wavelengths only; the spectroscope is able to spread the general white light of the sun into a band as long and consequently as diluted as one may please; but it can do nothing to dilute the pure bright images of the prominences in the lines characteristic of hydrogen. Hence with a good spectroscope the prominences may be seen and photographed at any time, without waiting for an eclipse, and in fact the record of prominences is included in the daily routine of a solar observatory.

This brings us back to newer methods of investigating how the vapours of hydrogen and calcium are disposed as "faculæ" in the atmosphere of the sun. The instrument employed is the spectro-heliograph, developed by Hale at Chicago and by Deslandres at Meudon. By means of two slits moving in

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unison it is possible to separate out the light coming from the vapour of a given element in a given layer of the solar atmosphere, and to produce, for example, a picture of the sun in hydrogen light from the upper layers or in calcium light from the denser lower layers just above the photosphere. The spectroheliograph opened out a wholly new line of possibilities, but the profusion of results, out-running the powers of interpretation in some cases, makes it impossible to sum up in a few words the clear gain which has resulted.

We study the sun because we are interested in all knowledge of the great power-house of the solar system; but also because the sun is in a sense a gigantic laboratory, where processes can be observed at temperatures, at pressures, and on a scale which cannot be imitated in terrestrial laboratories. In the sun may be found the answer to questions which can hardly be investigated otherwise, questions of the highest importance in physics and chemistry. How shall we account for the fact that hydrogen gives two spectra completely different, one of which can be produced easily enough in the laboratory, while the other cannot be produced at all, and is indeed recognized as belonging to hydrogen only by some curious arithmetical relations between the lines in one spectrum and the lines in

TIDES

another? Questions such as these may be solved some day by study of the solar atmosphere, conducted at a distance of more than ninety million miles from our observatories. Moreover, the sun is a star; and the only star which we can study in detail at close quarters. A thorough understanding of what is going on in the sun's atmosphere will lead us gradually, no doubt, to an interpretation of the many problems presented by stars of varying types.

As we pass from the sun to the moon let us glance for a moment at the tides, in the production of which the moon and sun play similar but somewhat unequal parts—the proximity of the moon considerably more than compensating for the much greater mass of the sun. Everyone knows in a general way that the tides are due to the moon—though it is on record that one observer became doubtful because he had sometimes noticed that there is a tide when there is not any moon! But the subject is complex and difficult; and the well-known figure, of high water under the moon, where the moon drags the water away from the earth, and another high water on the opposite side, “where the moon drags the earth away from the water,” is responsible for not a little misconception.

The crest of the principal tide wave pro-

THE SUN AND MOON

duced by the moon is not necessarily under the moon, but its position depends upon a number of conditions. Perhaps the best way to think of the tides is to imagine in the first place a free ocean, of uniform depth, unobstructed by land. Then the actions of the sun and moon, in their various configurations, combined with the rotation of the earth, would cause a number of tidal waves of various periods and different heights, and the effect at any moment is due to the combination of these waves. Their tendency to run round the earth is profoundly modified by the configurations of the land, which check the waves, and deflect them, and concentrate them in certain places, so that in different parts of the world the phenomena of the tides are extremely various.

Around the coasts of the British Isles the tides are somewhat exceptional, in that the two tides each day are approximately of the same height. In consequence the tides are not very difficult to predict with fair accuracy by the use of rather rough-and-ready methods. In other parts of the world—India, for example—the two successive tides are very unequal, and they vary apparently very irregularly. Far more scientific procedure is then required to predict the tides with the accuracy demanded by navigators in the Eastern seas. First, the

TIDE PREDICTION

tides, for a series of years, must be observed at various ports. Then the observed tidal curve must be analysed into its separate components by the method known as harmonic analysis. When that is done, the tides for future years can be predicted by a beautiful machine. Every year a series of pulley wheels in this machine are set to execute the oscillations prescribed for them by the results of the analysis. A cord passes over the whole series and carries a pen at the end. The machine is set in motion, and the pen, actuated by the combined motion of all the pulleys, draws in a few hours the predicted curves for the year, one after the other, for the principal Indian ports.

For its practical importance the study of the tides ranks with the most indispensable applications of scientific inquiry. Success in predicting the apparently haphazard, the really complex but orderly tides of a port such as Aden, is justly regarded as one of the triumphs of the theory of gravitation. But the most fascinating chapter in the theory of tides is the chapter in which Sir George Darwin traced the past and predicted the future history of the moon. The friction of the tides retards the rotation of the earth, so that the day is becoming longer by very slow degrees. By a process of reaction, the

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moon is by equal necessity driven away very slowly from the earth, so that the month becomes longer also. Carrying the process back, Sir George Darwin pictured for us a time when the earth and the moon were almost in contact, and the day and the month were equal, probably between three and five hours long. With the two bodies so close together the tidal forces were much more powerful and efficacious then than they are now; the moon was driven away, and the month was lengthened; the day was lengthened also, but not so fast; by slow degrees we arrived at the present condition, with a lunar month of 27·3 days. Looking forward, we are told that the day will grow longer more rapidly than the month; that in the far distant future the day and the month will be again equal, at about fifty-five of our present days; after which the moon will begin to approach gradually nearer and nearer to the earth until, if the heavens survive, her ultimate fate is to return to the earth from which perhaps she was formed in the beginnings of our system.

The most familiar result of these intricate tidal effects is that the moon turns the same face constantly towards the earth—not absolutely, for her varying motion in an elliptical path allows us to see occasionally a few degrees one side or the other beyond the usual limit.

LUNAR SURFACE

But, speaking roughly, we see always the same face of the moon, and are condemned to remain in ignorance of what may be on the hidden side. Let us, however, say at once that there is no probability that the side we cannot see is anywise different from the side which we can see. The speculations which have given the far side of the moon an atmosphere, water, vegetation, and inhabitants, have no justification whatever. When, after the lapse of millions of years, the effects of tidal friction allow future astronomers to examine at last the side which is hidden from us, we may feel sure that they will be disappointed if they expect to see anything more than the volcanic wilderness which the moon's near face presents to us. No trace of atmosphere survives upon the moon; a star passing behind the moon moves steadily up to the moon's limb without dimming or refraction, and at the limb, especially if it be the dark limb, the star goes out with a suddenness which never fails to impress the observer. No trace of cloud, no trace of the action of water in any form, can be descried now upon the moon's surface. No twilight mitigates the hardness of the black shadows cast in the intense sunlight, and it is not perfectly certain that any change has ever been observed in the exquisite detail which even a small telescope will show.

THE SUN AND MOON

The moon is the one object in the sky which may be shown to anybody without fear of disappointment. The exaggerated ideas which are current as to the power of a big telescope; the expectations that any casual observer should see as much as is depicted in the finest astronomical drawings or photographs, make it a matter of some uncertainty whether any other object will please or disappoint. The moon alone among telescopic objects looks immeasurably better in the telescope than any published representation; her beautiful silvery colour, the exquisite sharpness of the shadows on plain or crater floor, the brilliance of the mountain peaks as they catch the first rays of the rising or the last of the setting sun, cannot be reproduced upon paper.

The many excellent published photographs of the moon give, however, a perfect idea of the moon's features, if not of her beauty. Those features are in great part volcanic—or so we are prone to believe. The volcanic features are indeed upon a scale which is immense compared with the size of the moon, and they differ in some important respects from the generality of volcanic craters upon the earth. The perfect development of the central cone, the clean cut which one crater will make into the wall of a neighbour, and the immensely long, bright straight streaks

LUNAR CRATERS

which radiate from some of the principal craters, are features to which the earth's volcanic regions afford no very perfect counterpart. In considering how far such differences are significant we must remember the lesser power of gravity upon the moon, the absence of atmospheric denudation, perhaps also the absence of the steam which plays such an important part in volcanic action upon earth. Interesting and suggestive as are the theories which would explain lunar craters as due to the splash of meteorites, or the bursting of bubbles, it does not appear that there is much justification for refusing to believe our eyes, when they tell us so plainly that the moon is volcanic but that the volcanoes have long been dead and cold.

Two observations of recent years have thrown some light upon the moon's physical state. By a series of ingenious experiments Monsieur Lyot of Meudon, comparing the light of the moon with sunlight reflected from a wide range of terrestrial rocks and minerals, concluded that the only substance he could find on earth that reflected light like the moon is volcanic ash. About the same time two American astronomers of Mount Wilson, Messrs. Pettit and Nicholson, had the happy idea to measure the surface temperature of the moon before and during a total eclipse; as the edge

THE SUN AND MOON

of the earth's shadow passed across the centre of the lunar disc the surface temperature fell in a few minutes from $+ 178^{\circ}$ Fahr. to $- 152^{\circ}$ Fahr., which showed that the moon had not absorbed any appreciable amount of the sun's heat that had been falling upon it before the eclipse. Had the heat of the surface penetrated an inch below the surface, the cooling could not have been so rapid. The surface must therefore be formed of very badly conducting material, and the only material which suggests itself is volcanic ash which has precisely that property of insulation. The two inquiries conduct very satisfactorily to the same conclusion, but seem hard to reconcile with the general low reflecting and therefore high absorbing power of the lunar surface.

For the remarkable difference between the earth and the moon, or, so far as we can tell, between the moon and other satellites, no reasonable explanation has been given. The problem is a curious one when we regard the moon as a satellite of our planet earth. It is no less curious if we regard the earth and moon as twin planets moving together about the sun. One analogy may perhaps be mentioned here, though we must be careful not to press it far. Of late years we have become familiar with the fact that quite a large proportion of the stars are twin stars, and that the two

EARTH-MOON SYSTEM

members of the pair are often surprisingly different in their physical state. Is it perhaps possible that when one body separates into two—as we suspect has happened with the earth-moon system, and in the binary stars—there is a considerable sorting out of materials, so that the two bodies which are produced differ from one another very much in composition and in character? It may be so, though we cannot pretend to understand the mechanism of the process. And unfortunately nothing is happening now upon the moon's surface to give us any clue as to the processes which have gone on in the past.

To revert for a moment to our consideration of the sun: we were able to regard him as a laboratory in which we could study, though at a distance, the performance of experiments in physics upon a vast scale. The moon we must liken rather to a closed museum case in which the past is so to speak crystallized, hard, brilliant, and exquisite, but unchanging, and lacking, therefore, the fascination that belongs to continual change and reconstruction.

CHAPTER III

THE PLANETS AND THEIR SATELLITES

FOR many people there was 25 years ago just one question in astronomy: Is there life upon Mars? The possibility that astronomers might find in some other planet traces of intelligent life exercised a fascination that inspired the novelist, the dramatist, and above all the journalist. So the world became quite familiar with the idea that something or other had been found upon Mars which seemed to prove the presence of intelligent inhabitants. For Mars, at any rate, the question was considered almost settled: why else did a generous benefactor leave to the Paris Academy of Sciences a magnificent prize, to be given to the man who first succeeded in establishing communication with a planet *other than Mars?*

A rapid survey of the planets will show us why it is always Mars that is chosen for the abode of life. Mercury is very near the sun, must be very hot, and having no atmosphere can hardly be reckoned habitable. Moreover, Mer-

HABITABILITY OF PLANETS

cury is small and never gets very far away from the sun, and so is difficult to observe; and it is not certain that any definite markings have ever been seen upon his surface. Now, for any proof of habitation, definite markings are indispensable. Mere habitability as an abstract quality has little attraction for those whose interest lies in a search for evidence that life actually exists. And if we ask ourselves what kind of evidence would prove, or at any rate strongly suggest actual habitation, the answer seems to be that we must see something that looks unnatural, but can be interpreted with some reason as artificial. We must look, in fact, for evidences of intelligent engineering upon a gigantic scale.

From this point of view Mercury is hopeless; and the case is no better with Venus, though Venus is nearly the same size as the earth, is not impossibly near the sun, and has a large cloud-laden atmosphere that might perhaps, if not now, then in the distant future, make life as we know it tolerable there. Unfortunately it is just this atmosphere that makes it impossible for us ever to see down to the surface of the planet. None but the most vague and indefinite markings are visible upon the disc of Venus: so vague that it is not yet known what is the period of rotation of the planet. We are debarred from a sight of the surface, and from any possibility of detecting what may lie upon it. Hence, in our

THE PLANETS AND THEIR SATELLITES

search for inhabitants, Venus must be passed by.

Proceeding outwards beyond the orbit of the earth we come to Mars, and then to the zone of the minor planets. These small fragments of worlds have an interest all their own, but it lies remote from possibilities of habitation. Making up in number what they lack in size, the minor planets are at once an interest and burden—objects of that sporting instinct which prefers always to discover some body unimportant but new, rather than to work soberly at the known bodies which are from their great number an incubus to those whose duty it is to keep track of them, and to predict their places so that they may be observed. The time has long gone by for gratitude at the discovery of a new minor planet. Very early in their history they broke down the rule that every planet must have a symbol of its own—or, at any rate, they reduced the symbol to the simple form of a number enclosed in a circle.

In 1911 we remarked that the day was not far distant when those numbers would run into four figures and the circles would have to be elongated to hold them. The day came in 1923 when the thousandth planet was discovered by Reinmuth at Heidelberg, and the last number assigned in 1934 was 1,301. For long it has been impossible to maintain the rule that every minor

MINOR PLANETS

planet should have a female name drawn from classical mythology. Just a few are of peculiar interest by the peculiarity of their orbits, especially the possibility of close approach to the earth. Such, for example, are Amor, discovered by Delporte at Uccle in 1932, which can come within about 10 million miles of the earth; and the still more remarkable planet provisionally known as 1932 HA, which can come within 3 million miles, and was actually observed only $6\frac{1}{2}$ million miles away in May 1932.

They would give sensational opportunities of determining the solar parallax were they not so faint and moving so fast in the sky when they come nearest. There is no useful rival as yet to the planet Eros, which we shall discuss later, though Eros is no longer exceptional in having an orbit considerably inclined to the ecliptic, of decidedly elliptical form, interlacing the orbit of Mars, and on occasion approaching the earth within 15,000,000 miles. The discovery of Hidalgo, which travels out to the orbit of Saturn, or of Amor and 1932 HA makes us renew the inquiry whether we should think of such planets as properly belonging to the family of the minor planets, or rather as members of a distinct class which like the new satellites of Jupiter and Saturn seem to have been reserved for the purpose of upsetting preconceived notions in the twentieth century.

THE PLANETS AND THEIR SATELLITES

These planets are all so small that only three or four have measurable discs. The biggest are only a few hundred miles in diameter, and if we look for places where we may hope to find intelligent life, they are negligible. Their mathematical interest may be indicated very briefly. First, there was the question whether they were the remains of a large planet broken up ; the evidence is against it. Then came the question, why are they arranged in zones, with considerable gaps between the zones, and the answer to that is, that the gaps have been formed by the disturbing action of Jupiter and Saturn. Finally, of late years it has been found that some of these small bodies are so arranged that they provide beautiful examples of certain celebrated theorems in the problem of the motion of three bodies under their mutual attractions.

Passing on now to Jupiter, the largest of our sun's family, we perceive at once that as we cross the zone of the minor planets, we cross into a region where the planets are no longer terrestrial bodies, in the sense that they are something like our own earth, but are much larger, much lighter, almost certainly much hotter inside though very cold on the outer surface, and seem to belong altogether to a more primitive age, such as that which the smaller planets doubtless passed through long ago. The true surface of the planet is obscured by strongly

JUPITER AND SATURN

marked belts of cloud, flecked with bright and dark patches which change from month to month; and from year to year the belts change also, a single belt becoming double, or a pair coalescing to form one. At first sight it may be thought that this appearance is very much like what the earth must present from without, with its equatorial belt of clouds and its trade wind zones. But the cloud belts upon the earth, and consequently its appearance from without, vary with the seasons and repeat themselves pretty exactly year after year; while upon Jupiter there is little appearance of season, and the changes do not appear to repeat themselves after the lapse of Jupiter's year. We are forced to conclude that Jupiter is in a condition very different from that of planets which we may regard as habitable. If Jupiter has a solid surface, which is not altogether probable, it must be sunk so deep in the cloud envelope that the rays of the sun can never penetrate there, and we cannot regard it as fitted at present for life anything like our own.

As an abode of life the planet Saturn seems to be in worse case than Jupiter. The mean density of the visible globe of Saturn is less than that of water, from which we may, of course, conclude with certainty that we see nothing of any solid nucleus, which, if it exists, must lie far within the cloud envelope and can hardly be

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reached by the rays of the sun. It is idle, therefore, to speculate how the rings which encircle the planet, and the nine or ten satellites which accompany it, may look to the inhabitants on the planet's surface. These splendid appurtenances are thrown away upon an uninhabitable world.

Proceeding still farther outwards we come to Uranus, and then to Neptune, of which, as planets, there is little more to say than that they are large, each about 30,000 miles in diameter; that they are light in substance like Jupiter and Saturn; and that they show no detail upon their tiny discs. Neptune in a large telescope is of a fine green colour, which makes him readily distinguishable from the surrounding stars, and the spectroscope shows that both he and Uranus have large and dense atmospheres, that absorb some part of the sunlight falling upon them, before it is reflected back to the earth. More than that we cannot say of these planets on the boundary of our solar system.

The result of our review is, then, that no planet excepting Mars affords us any opportunity of scrutinizing its surface so closely that we may hope to find there any evidences of intelligent life. We may consider it very fortunate, therefore, that Mars—whose position next outside the earth's orbit allows us to study his surface to greatest advantage—is the one planet

HABITABILITY OF MARS

whose real surface seems to be open to our examination.

At first sight Mars is by no means unlike what we may believe the earth would look like if we could study her from Venus. Mars is smaller, indeed, than the earth, with a diameter not much more than half as great; but still Mars is amply large enough to be a comfortably habitable globe. And though the force of gravitation would be less there than upon the earth, and a man suddenly transported there would feel that his size and his strength were out of proportion to his weight, nevertheless we need not imagine that he would require any immense structural alteration to be adapted to the new conditions. Mars has an atmosphere—not, indeed, so dense as that of the earth, nor so laden with clouds and moisture—but still an atmosphere which can carry some amount of cloud, and which is not altogether too thin, we may believe, to allow of the existence of beings something like ourselves. In estimating such probabilities we must always remember how extraordinarily adaptable our own organisms are. To a native of the Congo the life which the Eskimo lead might very well seem impossible.

Mars has polar caps—not indeed so large as the polar caps of the earth, nor so permanent—but still caps of brilliant white which form in

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the winter and melt in the spring very much as if they were formed of snow or ice. The atmosphere is thin, but contains both oxygen and water-vapour.

Until something more than thirty years ago the drawings of Mars which were made at the telescope showed a distribution of light reddish areas, taken for land, and of greenish areas, which were supposed to be seas; and though the relative distribution of land and sea was a good deal different in its character from ours, there was no difficulty in accepting it as a reasonable arrangement which might serve very well the parts of water and land upon the earth. At that time no one had heard of the canals.

The canals of Mars were discovered by the Italian astronomer Schiaparelli at the very favourable opposition of the planet in 1877 when its two satellites were also found. Their discoverer was struck by their narrow straightness, quite unlike any features that had been seen before upon the planet, and he almost at once considered the possibility that these features might be artificial—an hypothesis, he affirmed, which is in no way impossible. For many years, however, they remained invisible to all but Schiaparelli; then gradually, with increasing skill, perhaps with increasing desire to see them, other observers succeeded. Sceptics

CANALS OF MARS

deny even now the existence of the canals, and affirm that they are visible only in virtue of a contagious enthusiasm and almost hypnotic suggestion. If that explanation fails, then they are ascribed to an alleged natural tendency for an observer to represent in the form of hard dark lines any fortuitous arrangement of minute and intricate detail very imperfectly seen. The canals, however, have been observed by many independent observers, who are positive that they are not deceived; they admit the difficulty of the observation, but maintain that at the rare moments when the air is really steady the canals come out clean and sharp.

They say, and apparently with justice, that critics who have never undergone the long training in observation, and especially critics who have never spent weeks at the telescope waiting for the occasional moment when a really fine climate gives really good seeing—those critics have no right to say what can or cannot be seen upon the disc of Mars.

We do not propose to decide whether the published drawings of Mars are representations of genuine detail or are untrustworthy guesses at something which really lies beyond the range of accurate visibility. It is far better to admit the whole of the evidence, and to see whether with that the advocates for life on Mars can prove their case.

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To do so they must establish two propositions:—

1. That the canals are not natural.
2. That if they are artificial they can be explained as serving a useful purpose, a specific purpose, which we can believe is valuable to intelligent inhabitants.

Now it is impossible to lay down hard and fast rules for distinguishing the artificial from the natural. A graceful piece of engineering which fits its surroundings, such as the railway bridge below the Victoria Falls, looks almost natural; a natural crystal may look exceedingly artificial. Hence to establish the first proposition must involve what is really an appeal to reasoned faith. If a man will not believe that a certain pattern is artificial, it is hard to make him do so; the most one can do is to point out that if it is artificial, it has a very natural interpretation.

The arguments, as they now stand, that Mars is inhabited, must always be associated with the name of Percival Lowell. He built his observatory in the hope of proving his point, and on the observations which proceeded from it he constructed an argument of high interest. His chief observations are these: The polar caps melt in the spring and a broad belt of dark colour surrounds the place where they have been. At that time the canals are invisible, but they soon

LOWELL'S THEORIES

begin to appear, and they appear in order, first those near the poles, then those in temperate, then those in equatorial regions. As Lowell puts it, with advancing spring in either hemisphere a wave of seasonal change sweeps down from the pole to the equator.

The second fact is that there are canals in the dark areas which were formerly supposed to be seas. In the summer they are not visible; but in autumn the dark greenish areas begin to turn brown—perhaps to dry up—and then it is seen that they are crossed by narrow dark lanes which remain dark when the regions they traverse have turned brown.

Further, it was assumed by Lowell, as a general principle, that planets tend to lose their water and to dry up. Mars, we are asked to believe, is now badly watered, and the inhabitants are put to great straits to live. Their atmosphere is thin; they have little rain; they have only one source of water-supply which can be utilized, and that is the flood of water released by the melting of the polar cap. The way in which the canals appear successively from the polar regions towards the equator is then quite simple. No one supposes that we see actually the canals themselves; but the effect of the flood, the burst of vegetation which turns the dusty fields to a deep green colour as the water is led over them. Such an effect would no doubt be

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visible to the inhabitants of Venus, if they could watch the Nile flood spread over the plains of lower Egypt.

The supposed proof of the existence of Martian inhabitants depends wholly upon this theory that the canals form a gigantic irrigation system, preserving the people for a time when their crops began to fail for want of water. Lowell nowhere explained how his irrigation system would work; yet there are several points which are, to say the least of it, somewhat obscure.

In the first place, if water is carried every spring from the pole to the equator, by the canals, it must return in the winter by the atmosphere; yet the polar cap forms so late in the winter and melts so early in the spring that it is impossible to imagine it of any considerable thickness, and very hard to believe that by its melting it can supply water for half a world.

In the second place, it is very difficult to believe in the possibility of carrying water in canals three or four thousand miles long. The waste by leakage and by evaporation would be enormous. By hypothesis the planet is becoming drier, and has lost the greater part of its water by absorption or escape. One must believe that those processes are active still. How then has the scanty supply which remained been saved

THE CANAL SYSTEM

from the fate of the rest, during the immense time occupied in constructing an irrigation system over the whole Martian world? No answer to this important question has ever been suggested.

We may doubt the engineering merit of the canals, which do not run down the meridians from the poles, but in many conspicuous cases prefer to go at a long slant towards the equator. Then comes the question of the dark spots at the junctions, which give the system an appearance like the conventional railway map. What are these round dark areas at the junctions? We are invited to believe that they are the naturally fertile regions whither people are attracted, and where they make their homes. Why then should they lie ten or a dozen in a direct line?

In fact, when one begins to examine the canal system as a working irrigation scheme one finds all kinds of features which are not to be explained as reasonably artificial. The works of man upon the earth are so restricted by the conditions which nature imposes that they must follow natural lines, and from a little distance they generally lose their crudely artificial look. But we are asked to believe that on Mars no natural obstacles have stood in the way of a perfectly geometrical design. Artificiality has grown up unchecked by natural restrictions.

THE PLANETS AND THEIR SATELLITES

We must conclude that we do not, with the best intentions in the world, understand how the irrigation scheme would work. "Very well," say its advocates, "that proves only that the Martians are more intelligent than you are!" But we are loth to admit that, as the final conclusion of the whole matter, and so we can say only that there is as yet no proof at all of the actual existence of intelligent life on any world but ours.

Discussing in 1911 the possibility of other planets beyond the orbit of Neptune, we remarked that it is not surprising that the romantic story of the discovery of Neptune should have fired other astronomers to emulate the achievement of Leverrier and Adams, who calculated the position in which Neptune was to be found from the existence of unexplained irregularities in the motion of Uranus. The motion of Neptune had been carefully scrutinized to see whether there are traces in it of disturbance by some planet yet farther from the sun, and more than one search had been instituted on more or less plausible grounds; but up to that time these attempts had met with no success, and it seemed likely that they were premature, for Neptune had then only just completed half a revolution in his orbit since his discovery in 1846. A more promising chance was to look for further irregularities in the motion of Uranus, left un-

PLANET PLUTO

explained after a careful examination of all that Neptune could do. If, however, an extra-Neptunian planet existed it was highly probable that it would be discovered some day, not by any kind of mathematical prediction, but by direct comparison of two photographs.

This forecast was doubly happy. Some years before his death, the enthusiastic and imaginative Percival Lowell had made or caused to be made an elaborate discussion of the residual errors in the motion of Uranus and Neptune, and had predicted that an extra-Neptunian planet would be found within certain rather wide limits in the sky. The astronomers at the observatory which he had founded at Flagstaff, in Arizona, devoted themselves energetically to the search and they found an extra Neptunian planet, Pluto, which they loyally claimed as in accordance with Lowell's prediction. There is little doubt that the prediction was badly founded, and the success due to enthusiastic hard work combined with good fortune. The opinion of E. W. Brown that the material discussed by Lowell was insufficient to give any definite result may be accepted as authoritative. Apart from that, one may well be of the opinion that the method of calculation was a characteristic misuse of the process known to mathematicians as the method of least squares. What is more, the planet Pluto is so faint that one

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cannot on any reasonable estimate of its reflecting power believe that it is anything like as big as the earth, and it would have to be much bigger to have a mass sufficient to produce any sensible disturbance in the orbit of Uranus. The conclusion is therefore that Lowell's prediction was ill-founded, and that the discovery was due to good fortune and not to theory. Nevertheless, one must allow that if the prediction had not been made, and if it had not indicated a region in which to search, the search would not have been made, and the planet which is very faint would not have been found. The cautious judgment of 1911 happened therefore to be right both ways.

That all the planets revolve in the same direction round the sun, and each family of satellites in the same direction round their respective primaries, was supposed, until a few years ago, to be one of the canons of astronomy, inevitable according to the nebular hypothesis, and necessary to the stability of the solar system. In the year 1905 the discovery that a new distant satellite of Saturn, named Phœbe, moving in a direction opposite to that of the others, excited great enthusiasm. The satellite had been announced by Professor W. H. Pickering, of Harvard, some years before. Nothing further had been heard of it, and its very existence became doubted, when an English astronomer

JUPITER'S OUTER SATELLITES

visiting Harvard brought back the news that a great surprise was in store. It came very quickly in the announcement that Phœbe's motion was retrograde. About the same time Dr. Perrine, at the Lick Observatory, discovered first one, and then another, new satellite of Jupiter, lying in paths far outside the older ones, highly inclined, nearly equal, and interlaced. They were put under observation at Greenwich, and in February, 1908, Mr. Melotte, of the Royal Observatory staff, discovered another, which, like Phœbe, moved in a retrograde orbit.

These capital discoveries were due to photography. The small bodies discovered are barely visible in the largest telescopes, and they lie so far from their planets that they are outside the range of ordinary observation. It is highly improbable that they would ever have been found visually, while to obtain photographs of them is arduous in the extreme. But it was imperative to get regular observations of Jupiter's eighth satellite, for its motion offers the most curious and fascinating problems. Of any other satellite one may say that it moves in an ellipse, and continues to revolve nearly in the same orbit for ever. Small modifications will be caused by the influence of the sun and the other planets, and the other satellites, but these changes are not large, and they balance one another after a

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time; the motion is said to be stable, which means in effect that the planet has an absolutely controlling influence over its satellite. The eighth satellite of Jupiter is so far away from him that this can scarcely be true for it. We may say that the satellite is always trying to get away from Jupiter and move round the sun as a planet—which is true of all satellites—but in this one case it comes pretty near to succeeding. The result of this is that the satellite describes a highly irregular curve which does not repeat itself in the least, and which defies all the usual methods of calculation. Very fortunately the methods which Cowell and Crommelin had applied with so much success to the motion of Halley's comet were all in working order ready to tackle the new satellite, which they did with complete success.

Having spent so much space on these distant satellites, we have but a few lines to give to the old. The theory of their motions, like that of our own satellite, is exquisitely complicated. As to their physical appearance, there is not very much to be said. Only the four satellites of Jupiter discovered by Galileo are large enough to show any visible disc. From the little that can be seen, it appears that they are belted, and that they rotate on their axes in the same time that they revolve about Jupiter. Whether, like our moon, they are barren and airless, has yet

PLANETARY EVOLUTION

to be determined. As objects for the smallest telescope, these four satellites have an unequalled interest. Their eclipses by the shadow, their passages before and behind the planet, their ever varying groupings, provide for us, as they did for Galileo, an object-lesson in celestial motions, which all may see and which none should miss. There are few to-day who would miss them deliberately, lest they should be compelled to believe what they are anxious not to believe.

In 1911 there was nothing useful to be said about the origin of the Solar System. But in 1917 the University of Cambridge adjudged the Adams Prize to Jeans for an essay on *The Problems of Cosmogony and Stellar Dynamics* which was published in 1919, and followed in 1928 by a larger volume *Astronomy and Cosmogony* whose Preface states that so much had happened in the intervening decade that a new book seemed to be called for rather than a new edition of the former. Our present knowledge of planetary evolution is contained in these two books, full of very difficult mathematics, but with the main conclusions kept apart and expressed with Jeans' accustomed lucidity. Very briefly his conclusion is that a passing star coming exceptionally close raised enormous tides in the sun, which resulted in the expulsion of a filament of matter which he likens to the shape

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of a cigar. As the disturbing star passed, the filament, being projected from the tidal wave which was running round the sun under the star, had a considerable velocity of rotation round the sun. It condensed into the planets, the largest in the middle, the smaller at each end, conforming to the cigar-like shape. The explanation and the analogy must not be pressed too far. Jupiter has a mass more than all the other planets put together, Mars coming between the earth and Jupiter is too small for its position; and the zone of minor planets is the difficulty in this theory as in most others. But roughly speaking the theory fits the facts much better than any other and is supported by mathematical reasoning that few could dispute. The author proceeds to calculate what are the chances of so close an encounter between two stars, and concludes they are so small that our solar system may be the only system of planets in the universe, and that at any rate they should be excessively rare.

The systems of satellites are miniatures of the system of planets, and we naturally look to a similar cause for their formation, but it is not possible to see very far.

Belonging to the same inquiry is the question first raised by Roche, whether there are limits to the nearness at which a satellite may circulate about its planet, without becoming broken

ROCHE'S LIMIT

up by analogous tidal disturbance. Roche published his theory at Montpellier in 1850, and his results so far as they go are entirely supported by Jeans, even to a close confirmation of the numerical result, that the motion of a satellite cannot be stable if its distance from the planet is within 2.45 radii of the planet when the densities of the two bodies are the same. The outer edge of Saturn's ring is within this limit and the fact suggests that the ring is formed from a satellite which became unstable and broke up. The continued existence of the innermost satellites of Mars, Jupiter, and Saturn at distances not much outside the limit seems to add strength to the argument. But Jeans remarks that the figures have no significance unless the planets and the satellites have the same density, and in fact the densities are likely to be so different and always to have been so different that the figures have little importance. If that is so it seems rash to suggest, as he does elsewhere, that the minor planets are fragments of a larger which came within the danger-zone of Jupiter.

All this is very different from the celebrated nebular hypothesis enunciated by Laplace, but never very clearly developed. He supposed that a condensing mass of gas shed rings which condensed into planets, and some of the photographs of nebulae have been adduced as support-

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ing this idea. But now that we look upon the nebulae as complete galaxies it is difficult to give any importance to an apparent similarity on such a greatly different scale.

CHAPTER IV

COMETS AND METEORS

A COMET and an expected shower of meteors were responsible for two great public disappointments. The famous Leonid meteors, which in 1799, in 1833, and in 1866 provided displays of a grandeur never forgotten by those privileged to see them, were due to return in 1899 or 1900, and they failed to appear in any considerable numbers. Halley's comet—famous in the history of the world, and not less renowned in the particular history of astronomy—was awaited in 1910 with a degree of interest without parallel in our recollection. In Britain and in northern latitudes generally it proved a miserable object in the light evenings of early summer, low down in the southwest with its tail lying at a small angle to the horizon; and it was hard to credit the accounts cabled from the south of the tail of the comet stretching from horizon to zenith like a gigantic searchlight.

The great public interest which Halley's comet aroused, the extraordinary precision

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of the prediction of its return, and the remarkable work done by Cowell and Crommelin in tracing its past history, rendered it inevitable that we should make this comet the leading theme in a chapter written in 1911 before it had passed completely from sight. Halley's comet is unique. There are many comets which have made a splendid appearance, and have passed never to return, or to return after so many thousand years that we may as well say never. There are many comets which return regularly to the sun at intervals of comparatively few years ; but they are faint and undistinguished things, hardly, if at all, visible to the unaided eye, and never likely to cause public excitement or to be taken as heralds of war and the death of kings. Halley's is the one comet which is periodic, coming back again and again, and is at the same time a magnificent object, a comet of the first class, worthy to play the spectacular part which it has in fact played for more than two thousand years of history.

Halley, by whose name the comet is known, was a man who, more than most, deserves a biography—which has not yet been written. The scattered references to him in the early history of the Royal Society picture for us a man of excellent capacity, energy, and common sense—not a profound philosopher, but one

EDMUND HALLEY

of those equally valuable people who have the faculty of undertaking the right thing and making a success of it. At an early age he was sent in command of one of his Majesty's ships on a long voyage to study the deviation of the compass in different parts of the world. Later we find him Secretary of the Royal Society, active in promoting inquiry of all kinds, and particularly interested in the problem which was then unsolved, What causes a planet to describe an ellipse about the sun? Halley made a journey to Cambridge in the confidence that if anyone could throw light upon the matter it would be Newton; to his delight he found upon arrival that Newton was already in possession of the theory. But that eminent philosopher does not seem to have had any ambition to publish his great discovery to the world. It was Halley who urged upon him the importance of writing the book which became the immortal "Principia." It was Halley who persuaded the Royal Society to publish the book, Halley who paid for it out of his own pocket, and Halley who occupied himself with applying the new theory of gravitation to calculating the orbits of comets, while Newton had become Master of the Mint and was refusing to "be dunned and teased by foreigners about mathematical things, or to be thought by our own people to be trifling

COMETS AND METEORS

away my time about them, when I should be about the King's business."

It must be remembered that when Halley began his work, no one had the least idea that a comet could reappear after a period of years. Newton himself had actually scouted the suggestion that a comet seen on one side of the sun might be identical with another seen some weeks later on the other side. Halley calculated the paths of twenty-four comets—all that he could find sufficiently observed—and of these three moved in orbits which were very nearly the same. Was it possible that they were the same comet returning again and again to the sun? There was a grave difficulty in believing it possible. The intervals between the successive returns were not equal. Between 1682 September 4, and 1607 October 16, was a period of 74 years 11 months; between the latter date and 1531 August 24, was 76 years and 2 months. Now if a comet returned again and again to the sun, it must be to all intents and purposes a planet; and if so, why did it not perform its revolution in a regular time? In seeing the answer to this difficulty Halley showed how keen was his intelligence; it might be the disturbing attractions of the planets which caused the irregularities in its reappearance. Satisfied with this solution of the difficulty, Halley staked

HALLEY'S COMET

his reputation upon a prediction that the comet would return again in 1758. He knew that he could never live to see the truth of his prediction; but in a fine sentence, often quoted, he expressed himself content with the faith that impartial posterity would not refuse to admit that this was first discovered by an Englishman.

Two circumstances of the last return in 1910 are noteworthy. So accurate was the prediction of Cowell and Crommelin, that the comet was found within two seconds of arc of its predicted place, on the first photograph which showed it in 1909 August. It had made the most rapid revolution on record. Between 1759 March and 1835 November was 76 years 8 months. If it had traversed exactly the same path again, it would not have been due at perihelion until 1912 July; whereas it actually reached perihelion in 1910 April. This acceleration of 27 months was explained as the effect of a near approach to Jupiter in 1835. The disturbance then impressed upon the path of the comet had little time in which to affect the date of the 1835 return, but its effect was felt throughout the succeeding revolution, with the result that the comet made its record passage, as we have said. Its actual return to perihelion, as observed in 1910, differed by 2·7 days from the prediction

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—an insignificant error, one might suppose, in so immense a prediction. But the authors were not satisfied. They repeatedly checked their work, and they are able to affirm that if the theory of gravitation is rigorously true, and no forces except gravitation act upon the motion of the comet, then not more than a fraction of a day can be attributed to defects of calculation. The balance of some $2\frac{1}{2}$ days can be explained only by the existence of forces which are not pure gravitation.

The second circumstance which made the last return of Halley's comet noteworthy was the passage of the comet across the plane of the earth's orbit at a point exactly between the earth and the sun. If the comet's head were large and solid, we should have seen it projected as a dark body against the sun; but nothing was seen; nothing was photographed. If the comet's tail had been straight, the earth would have passed through it, and this probability gave rise to a quite remarkable excitement. People who should have known better predicted that we should be asphyxiated by poisonous gases. Some cautious people laid in bottles of oxygen to sustain life during the fatal night. One or two committed suicide to escape death from the comet. And after all, nothing very much happened to the earth, perhaps because the tail was not straight.

HALLEY'S COMET

There were in fact at least two tails. As the time for the passage across the sun approached, the comet in the morning sky, before sunrise, became each day a more wonderful object to those observers, south of the Mediterranean, who had the good fortune to see it in a clear dark sky. As the comet closed up to the sun its tail grew longer till it reached the zenith. The day of the transit passed, and next evening the tail was seen, as was expected, in the west. But the following morning, quite unexpectedly, it was still visible in the east. There must have been two tails, and that night the earth was between the two.

Before we turn to the discussion of other comets, let us glance for a few moments at some features of interest in the work of tracing back into the remote past the history of Halley's. We have seen already that the comet returns after periods which vary by a couple of years on each side of seventy-six years. That makes it impossible to go back by a simple series of subtractions, to say that Halley's comet should have appeared in such and such a year, and to search the chronicles for records of a comet that will more or less fit the date. We have, in fact, to perform two distinct operations. First, from the recorded path of a comet among the stars, we must calculate its orbit and see if its position can be reconciled

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with the path of Halley's. Next, having made a preliminary identification, we must examine whether the actions of the planets can account for a return at that particular date. For the first step the European chronicles are useless. They tell that a comet appeared, and they usually attribute to it whatever disaster, pestilence, or illustrious death took place about that time. But they tell nothing of how the comet moved among the stars; they give us no details by which we can calculate even roughly what orbit the comet pursued. To gain the information we want for this purpose we must go to the Chinese annals, the dynastic histories and the great encyclopædias of ancient wisdom. From these records Hind was able to trace the appearances of comets which might very well have been Halley's, as far back as 11 B.C. It remained for Cowell and Crommelin to examine whether these dates were consistent with the calculated duration of each revolution, when perturbations by the planets are taken into account. This formidable task they completed with success, showing that Hind's identifications were nearly all correct—that it was Halley's comet which is represented in the famous panel of the Bayeux Tapestry; that it was Halley's comet which is pictured in the Nuremberg Chronicle for the year A.D. 684; that it appeared about the

HALLEY'S COMET

time of the battle where Attila the Hun was defeated by the Romans and the Goths. Halley's comet was the sign in the shape of a sword which hung over Jerusalem before the destruction of the city by Titus; it hung over Rome in 11 B.C. before the death of Agrippa.

Thus are comets remembered in history by the disasters which are ascribed to them, and the terror which they caused, when it was supposed that they swept through the upper air, almost within reach. By proving that at any rate they are far beyond the moon, Tycho Brahe rendered the world a service for which mankind should be grateful—those who have not still a lurking dread of what they fear a comet may bring. These were the reflections proper to the year 1909, when Halley's comet was approaching—a quiet satisfaction that we lived in enlightened days. The year 1910 came bringing with it a brilliant comet all unexpected; in January the people of Paris watched the so-called "Day-light comet" reflected in the great flood of the Seine which threatened to destroy their city; in May, while the people of London watched for Halley's comet, the body of King Edward the Seventh lay in state at Westminster. What wonder that the imagination seizes upon these deplorable coincidences.

Leaving now the historical side, let us see

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how far it is possible to understand what a comet is, and how its extraordinary phenomena are produced. The formation of the tail was well shown in the comet of 1882, which passed so close to the sun that it nearly grazed the solar surface. In three and a half hours the comet described 180 degrees of its orbit. One morning the tail stretched a hundred million miles in the east; the same evening it was a hundred million miles long in the opposite direction. Now it is impossible to suppose that the head of the comet swung that tail round through 180 degrees in a few hours; it is certain that the comet discarded its old tail and made a new one. With the advent of photography it became possible to study the tail in greater detail and more completely. Bright patches in the tail, photographed on one night, were replaced by other patches on the following night, but it was impossible to trace any detailed connection between one series and the other. Very often a comet is so near the sun that not more than one picture can be obtained each night. But occasionally a comet may be photographed several times in one night, and then it becomes possible to see what is really happening in the tail. The bright patches are travelling very fast along the tail, in the direction away from the sun. They tell us that the whole tail is being re-

PRESSURE OF LIGHT

newed continually by some influence proceeding from the sun, and that every comet's tail is practically new each day.

To explain such a surprising fact is not easy, but we have now at least a partial explanation, whereas thirty years ago one could say only vaguely "electric repulsion," which did not work out very well. It became possible to speak with some confidence of the part which the pressure of light may play in the formation of comets' tails, when an American professor came to Cambridge with a "comet's tail" sealed up in a glass tube. By a beautiful piece of experimenting Messrs. Nichols and Hull were able to show in actual operation the process that Maxwell had seen with the mathematical eye many years before. The experiment was this: the finest sand, and a very fine light vegetable powder, lycopodium, were mixed, and put into the top compartment of a tube like an hour-glass, which was then exhausted of air. Through a small aperture the stream of powder could trickle into the lower compartment of the glass, across which a concentrated beam of light was passed. The dense, comparatively large grains of sand dropped through without deflection, but the smaller and lighter lycopodium was swept against the side of the tube by the pressure of the light falling on it.

COMETS AND METEORS

Now it may be that a comet's tail is formed in this way. Light pressure would account for the fact that the comet's tail is always turned away from the sun, the powerful source of light. As the comet approaches, the tail streams behind; as the comet recedes, the tail goes before; so that evidently the source of repulsion lies in the sun. But light pressure does not explain how the comet's nucleus produces the fine dust, in the first instance—a part of the question to which perhaps insufficient attention has been given. In the second place, light pressure does not explain why or how the dust can remain luminous during the hours in which it is being rushed through space literally on the wings of light nor why it should exhibit the spectrum of a carbon compound. And thirdly, light pressure does not fit in particularly well with the measures which have been made of the actual accelerations of bright patches along the tail. In fact, the explanation by light pressure does not work out in detail quite so well as had been hoped.

In particular it does not really explain the fountain-like envelopes that are seen, in the telescope, surrounding the bright nucleus of a good comet. These envelopes were particularly remarkable in the head of the great comet of January 1910. At first sight they suggested very strongly that fountains of

COMET'S TAILS

brilliant particles were ejected towards the sun from the nucleus, and meeting the pressure of light were deflected and turned back into the comet's tail. A very complete study of this action has been made by Eddington from the wonderful series of photographs of Comet Morehouse (1908) made at Greenwich with the 30-inch reflector. His conclusion is that the explanation is certainly incomplete. Calculation shows that very variable and very large light pressures are required, while we find no sufficient explanation of the multiple envelopes. In fact, with our present limited knowledge it is difficult to make the theory work; while it is a serious embarrassment to remember that light pressure has no effect upon gas, but only upon solid particles; for the evidence of the spectroscope certainly seems to show that the tails are gaseous.

Now let us turn to the composition of comets. It is generally supposed that the nucleus of a comet very much resembles a swarm of meteorites. The connection between comets and meteor streams is certain. Several well-known streams of meteors travel in orbits which are identical with the orbits of known comets. In one celebrated case a comet has been seen to break up and disappear, and afterwards a bright shower of meteors came from the path in which the comet had moved.

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Yet it may be putting the connection too positively to state, as it has been stated, that "Biela's comet was shedding over us the products of its disintegration." There does not seem to be any definite evidence that the material which makes the comet's nucleus is the same as the material which flashes into the atmosphere of the earth and blazes for a moment as a shooting star. Indeed, the spectroscope shows that the light proceeding from the nucleus is often from sodium or other metallic vapours; while Fowler was able to produce in his laboratory a spectrum exactly corresponding to the spectra exhibited by many comets' tails, and has shown that it belongs in all probability to an oxide of carbon. In brief, then, the light of comets proceeds chiefly from a few metals and certain compounds of carbon; and it cannot be said that we have as yet any precise idea how these compounds are carried by meteors in the comet's head, nor yet why light pressure or any other form of radiation from the sun should be capable of lighting up the tail in so magnificent a way. When a comet goes very near the sun, we can imagine all kinds of violent actions upon it. But many comets—Halley's for example—do not approach the sun very much nearer than does the earth. How then, by what mechanism, by what internal energy, or by

METEOR SHOWERS

what method of extracting energy from solar radiation of any kind, does a comet shine with so brilliant a light, when planets may pass through such radiation without experiencing any very noticeable effects?

Since the great year 1910 there has been no comet of the first class, and no lesser comet has atoned for its want of splendour by exhibiting any very striking novelties or being so favourably placed that it could be studied at leisure, so that our knowledge of comets has remained nearly stationary, and nothing has happened to throw much light upon the difficult questions of their composition, the way their tails are produced, or their connection with the meteor streams which sometimes move in their orbits. But this last connection was emphasized by the brilliant and entirely unexpected shower of Quadrantid meteors that startled Europe in October 1933. A shower which was perhaps as rich as any of the famous Leonids came from a radiant that seemed clearly connected with the orbit of a faint comet named after Giacobini; so to remind us emphatically that the problem is always there, however little we seem to do to solve it.

We have spoken of brilliant comets, in which it is possible to see some structure, and which give light enough for analysis. The ordinary small telescopic comet, of which

COMETS AND METEORS

we have four or five a year, has little interest except the interest of calculating its path, finding whether it belongs to the solar system or is a casual visitor, and watching to see that it strictly obeys the law of gravitation. That is to say, its interest is not physical, but almost entirely geometrical. It may be of interest to describe the history of a typical telescopic comet, so far as we are concerned with it.

A few astronomers devote clear nights when the moon is absent to comet-seeking. The more fortunate have an instrument specially designed for the purpose, which allows an observer to sweep broad areas of sky without changing his position. He sweeps and picks up nebulae, which must be identified from the catalogues or observed until it is certain that they are not moving among the stars. After wasting very many hours with nebulae, a fortunate observer discovers a faint object, almost invisible, which is not catalogued as a nebula, and which in the course of an hour has moved perceptibly among the stars. It is a comet, unless it is a minor planet. The observations made at the beginning and end of the hour serve to give the position of the comet at the instant of the first observation, and a first rough estimate of the daily motion. A hasty search through the astronomical

DISCOVERY OF COMETS

journals shows that it is not a comet already announced, or one whose return is expected. It may be new, and it may have been discovered by another observer the night before.

The observer's duty is to communicate his discovery to other astronomers as soon as possible, that there may be no delay in getting to work. A telegram is sent to Copenhagen, where there is an organization for circulating astronomical news without delay, to all subscribers, in a special code designed for the purpose. Should the discovery have been made in the early hours of the night it is actually possible to send the news to Denmark, get out the code cable to America, and have the comet observed that same evening at some western observatory. Within a few hours, then, other observations of the comet may be secured and cabled to Copenhagen, which sends out again the earliest second observation received; and all the subscribers have now two places of the comet available. Directly a third is observed the comet's orbit can be calculated; so there is some competition to get the third observation. When it is obtained the fortunate observer should be prepared to call up all available assistance and to proceed straightway with the calculation of a parabolic orbit. Eight or ten hours' continuous work will finish it, and perhaps provide a little ephemeris or

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prediction for the next few days. Then for the first time it is possible to say what will happen—whether the comet shows any promise of becoming brilliant, whether it will be visible for long, and what constellations it will traverse. The elements—that is to say the numbers which define its orbit—and the ephemeris—the numbers which define its apparent path—are telegraphed to the Central Office, and sent out this time upon a “jellygraphed” post-card.

Time passes; the comet is passing beyond our range of observation; and there is some competition to secure the last observation. In a few months all the observations obtained are published in the various astronomical journals, and it is time for some one to announce that he proposes to undertake a definitive determination of the orbit—a determination, that is to say, which shall take account of all the niceties which were neglected in the first hurried calculations. The definitive orbit tells us whether the comet belongs to the family which have been captured for the sun by Jupiter, and it provides the means of rediscovering the comet at its next return, perhaps some five or six years afterwards. Before the next return a “search ephemeris” is calculated and published as a guide to rediscovery. Again there is some emulation, to be the first

ENCKE'S COMET

to pick up the faint object as it approaches the sun and grows gradually brighter.

The interest in these faint comets is thus almost entirely mathematical. They furnish beautiful exercises in calculation and admirable tests of the completeness of theory.

Once in a while a comet will be lost—it has made a near approach to Jupiter or Saturn, and has been deflected violently from its path: sent out of the system by a reversal of the process which may have originally captured it from outer space, or turned into a new path having so little affinity with the old that only a complicated calculation could show the connection. Thus these faint comets afford puzzles and problems which are some of the most elegant in astronomy. In particular they become beautifully intricate in such a case as that of the celebrated comet Encke, which approaches very close to the planet Mercury, and suffers besides from an acceleration to its motion, exceedingly difficult to explain—especially since it was shown by the elaborate investigations of Backlund that the disturbance changed its value suddenly three times in the last century. But we have no space to deal with the problem of Encke's comet. We must pass to the meteor showers, with which comets are closely allied.

The point which strikes us first as we con-

COMETS AND METEORS

sider the question of meteors, is that we see only the final catastrophe, and know nothing except by inference of the events that lead up to it. A bright streak of light across the sky, perhaps if the meteor is large a train of sparks which persists for a few seconds, and the career of the meteor is ended. It volatilizes with the heat engendered by its rush into the air, and eventually settles down upon earth as the fine meteoric dust which has been recognized in samples from the deep sea bottom. One might think it hard to discover very much from an observation so momentary; but by patient observation and comparison of results it is possible to deduce a good deal. The important fact to be observed is the direction of flight, which must be plotted on a star map or globe. As tracks accumulate it is seen that they are not at random. A certain proportion of those observed on any one night, or on corresponding nights in different years, will be found to radiate from a single point or small area. From this we draw the conclusion that the meteors, before they collided with the earth, had been moving in parallel paths, coming towards us from that point of the sky in which the radiant is situated. We have now information as to the orbit of the meteors: it passes through the point which the earth occupied at the time of observation—which

LEONID METEORS

can be taken out of the tables—and it passes through that point in a certain direction, given by our observations. Without going further into the details, we may say that in some cases, though not in all, it is now possible to calculate the actual orbit of the meteors. Thus, Newton (of New Haven, Conn., U.S.A.), in the middle of last century, found that magnificent showers of meteors were recorded in history at intervals of 33 years, identified them with the shower of Leonid meteors—that is, meteors radiating from the constellation Leo—and predicted their return in 1866. This prediction was a brilliant success. An immense shower of meteors was seen in November of that year, and a scarcely inferior display in the following November. Newton showed that there were five possible orbits in which they might be travelling; Adams proved that the largest orbit was the true one; and Leverrier found that this path took them so close to the planet Uranus in the year A.D. 126, that it is very probable that the whole shower was captured by Uranus and introduced to the solar system at that date.

Everything being thus completely worked out, one expected with some confidence a return of the great shower in 1899 or 1900. As the time approached, however, some calculations published by Johnstone-Stoney and

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Downing suggested the probability that the meteor stream might have been perturbed so much by the action of Jupiter that its path would no longer intersect the path of the earth, and thus we should have no display. It was impossible to be certain, for there was no means of estimating the size of the swarm, and the prediction of failure did not attract as much attention as did the general expectation of a grand display. Hence, when the shower provided no more than the usual scattering of meteors seen every November, there was great disappointment, and some mockery of the science which claims to be the most exact of all sciences. As to the mockery, it is often forgotten that many astronomical events cannot be predicted with the certainty of an eclipse or an occultation. They are expected, in the sense that it is advisable to look out for them; the expectation is, or should be, accompanied by a clear statement of the certainty or the probability of failure involved. Doubtless the warning will be neglected; the newspapers will magnify the expectation, and there will be disappointment, as there was with Halley's comet and with the meteors. All that the astronomical prophet can do is to be moderate in his promises, and cautious how he excites public interest. In the years about 1933 there was again the possibility of a great shower of

STATIONARY RADIANTS

Leonids, but prophecy this time was reserved, and there was little public but some scientific disappointment when nothing unusual was observed.

In comet-seeking and in meteor-observing there is a wide field for the enthusiastic non-professional astronomer. Now that there is no longer a substantial prize in money for each comet discovered, it is not possible to subsist upon comet discovery, as a very distinguished astronomer did for some time, in his amateur youth. But the possibility of attaching one's name for ever to a well-remembered comet must stimulate enthusiasm, and is in truth a very real though unsubstantial reward. How much was the fame of Donati increased by his discovery of the comet which at first promised badly, but manifested itself in the end as the most beautiful of its kind. In a less ambitious way, but one which offers more continuous employment, the amateur observer, with no equipment but a star map, can do very valuable work in the observation of meteors. There are still important matters to be settled, and some doubts to be resolved. Take, for example, the question of the "stationary" radiant points. If a shower of meteors is active on several successive nights, the radiant point should, in theory, shift a little each night. The August meteors from Perseus

COMETS AND METEORS

do show this shift. It is alleged by some observers that other showers do not, but that their radiant points, in defiance of theory, remain stationary. Now this is a question which must be settled; one of the principal difficulties in so doing is to decide what constitutes a radiant point. Two meteors cannot, for their paths produced backwards must meet in some point. A third passing through the same point suggests a real radiant, but it is much more difficult to decide if the third passes, say, two degrees away from the intersection. How much may we allow for errors of observation, and how much for a possibly real diffuseness of the radiation? That involves questions which are not easy to answer, and it is certain that there is great scope for the patient observer of shooting-stars, in elucidating this curious difficulty. Moreover, the trained meteor watcher knows his stars well, and has the best chance of picking up a "new" star.

One word more, as to the nature of meteors, or shooting-stars. We may be surprised at the minute size of the bodies which can produce for the moment so brilliant an effect. The ordinary shooting-star weighs not more than a grain, but it enters the atmosphere with a planetary velocity, and in a brief instant its energy of motion is all changed by friction of the air into energy of light and heat. And

METEORITES

bearing this in mind we may see in each meteor an illustration of the principle which was once invoked to explain the maintenance of the sun's heat, that arrest of motion means the production of heat.

Occasionally a meteor of large size, entering the atmosphere slowly, because it is overtaking the earth, will escape vaporization, and will fall to the ground. It can then be examined and analysed, and in a great number of cases this has been done. In no case has there been any evidence of the presence of an element not found in the crust of the earth. Space then, if filled with flying fragments of matter, is filled with quite ordinary materials.

They do, however, exhibit a composition like nothing else on earth, which must be seen to be believed. In the gallery of meteorites at the Natural History Museum one may study the most unlikely looking objects: conglomerates of stony fragments with lumps of iron embedded, that were at any rate never formed by the condensation of vapours in outer space, any more than a plum pudding could be formed by the chance collision of its various ingredients in a cyclone which had destroyed a grocer's shop. These at any rate must have been fragments of a large body, and of very curious composition. If they are fragments ejected from planetary volcanoes, why not from early

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volcanoes upon the earth? The problem was discussed by Sir Robert Ball many years ago in a paper published by the Royal Irish Academy, which gave excellent geometrical reasons for thinking that a meteorite which comes back to the earth is much more likely to have left the earth at some earlier time than to have been thrown out from another planet.

The lumps of iron which have been found upon the earth and identified as meteorites by their peculiar crystalline structure, and other significant details, are more numerous by far than the stony meteorites. On the other hand, the meteorites which have been seen to fall are mostly of the stony kind. Probably these are more likely to disintegrate by rain and frost, or are not so readily recognized as meteorites when they are turned up by the plough. But if we believe that the meteorites were ejected from the earth by early volcanoes, one may wonder whether some of the greater masses of iron found lying on the surface were not thrown sufficiently hard and fell back upon the earth.

The recent discovery of meteorite craters upon the earth is, however, rather against this speculation, because such craters show that meteorites of considerable mass have certainly fallen from the sky.

For many years there was just one crater

METEORITE CRATERS

upon the world, in Arizona, that was thought to be a meteorite crater. The neighbourhood is strewn with fragments of meteoric iron. But sanguine miners have failed to find by boring within the crater that principal mass of iron which they had sought at great expense, without reflecting that if they found it there was no way of cutting it up and carrying it away. The bottom of the crater is crushed quartz; the strata round the rim are tilted up as if by an explosion. But so long as there was only one object of the kind there was room for doubt whether the crater had been formed by explosion due to a blow from a meteorite.

Within the last few years several undoubted meteorite craters have been found: one in the great Southern Arabian desert by Mr. Philby, with very remarkable deposits of silica glass from which an excessively fine steel dust can be extracted, evidently the condensation of vaporized iron. At Henbury in Australia there is a whole group of craters with many fragments of meteoritic iron; while upon the island of Oesel, in the Gulf of Riga, there is a crater from which no meteoritic material has ever been obtained, but which was so evidently formed by a violent explosion that the impact of a meteorite is the least improbable cause. These craters are recent geologically, but not in any other sense. There is, however,

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one quite recent and sensational example of a meteorite fall in Siberia. In the summer of 1908 sensitive recording barometers registered one day in England a sudden jump in the atmospheric pressure, for which there was no explanation. Some years after the war there came at last reports of a great explosion which had followed the fall of a meteorite in the very inaccessible swampy forested country of the Stony Tunguska, and by good fortune the date was recognized as immediately preceding the unexplained barometer wave. Around the supposed place of fall the forest is devastated for miles, the trees thrown down outwards, and scorched upon the side towards the centre. There was unquestionably a very violent explosion, the greatest perhaps which has ever occurred in living history, and it is difficult to find any explanation for it other than a meteorite.

In general it would seem that a large meteorite hitting the earth and penetrating a little below the surface, suddenly vaporizes the sub-soil moisture, and an explosion of steam reinforces the explosion due to the vaporization of the meteorite. Fragments of the mass may be found outside the crater, but nothing within. The explosion crater is very much larger than, and completely destroys, the scar of the original impact. This ex-

METEORITE CRATERS

planation fits the observed facts more or less, some better than others. It does not fit at all the curious group of parallel ellipses in South Carolina which had been claimed as meteorite scars.

CHAPTER V

MOVEMENT UNDER THE LAWS OF GRAVITY

THE claim of astronomy to be considered the most exact of all the sciences rests, in popular acceptation, upon the seemingly miraculous way in which the astronomer makes predictions which come true to the second. At the moment of writing several parties of astronomers are planning expeditions to stations in Siberia and Japan, to observe a total eclipse of the sun. They know the moment when the shadow of the moon will come sweeping across the earth and strike them, and they know for how many seconds it will envelop them. If the eclipse were due a hundred years hence instead of within a few weeks of the time of writing, the prediction could be made with almost equal accuracy; while if it should by chance be a matter of historical interest to determine whether an eclipse of the sun were visible in that island two thousand years ago, it could be done.

Now let us consider for a moment what this involves. The moon is moving round the earth,

NEWTON'S LAWS OF MOTION

and both together are moving round the sun. At each instant the motion of the moon, which were it not for the sun would be very nearly a simple elliptic motion round the earth, or were it not for the earth would be very nearly a simple elliptic motion round the sun, is distracted by the competing attractions of both, and by the feebler but by no means negligible disturbances produced by the attractions of the planets. The task of the mathematical astronomer has been this, that starting with the simple Newtonian law of gravitation—every particle in the universe attracts every other particle with a force depending directly upon the product of the masses of those particles, and inversely as the square of the distance between them—he has to disentangle this infinite number of actions, to calculate the path which each body will describe, and the way in which it will be gradually modified with the lapse of time. He must weigh each body by studying how it affects the motion of other bodies; he must reduce the whole infinitely complex and laborious calculation to such a shape that it can be performed by companies of calculators who do not understand the theory of what they are doing, but execute an array of specified operations according to fixed rules. Finally, he must organize this arithmetical machine so that it can produce year by year, three or four years

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in advance, the numerical boiling down of all this mathematics and arithmetic in the form of a Nautical Almanac—or as it is more properly termed, an Astronomical Ephemeris or prediction.

In its most general form the “problem of three bodies” is insoluble by any mathematical processes that have yet been invented; in other words, if only the three bodies, the sun, the moon, and the earth existed, it would still be impossible to obtain a solution of the problem—what will be the motions of these three bodies under the influence of their mutual attractions. Still more, then, is the problem insoluble when, instead of three, we have a great number of bodies involved. There are, however, in the solar system certain simplifying conditions. The sun is very much more massive than any of his planets; the planets are at great distances from the sun; they move in paths which are approximately though not accurately circles; and they all move round the sun in the same direction. All these special conditions modify the problem so immensely that it is found possible to construct a theory which can deal in a laborious but sufficiently accurate and thorough manner with the actual problems that are presented to us in the solar system. The principal solutions which have been obtained are respectively the Lunar Theory, dealing with the motion of the

LUNAR THEORY

moon, and the Planetary Theory, which can be applied separately, with suitable modifications, to the motions of the planets.

Let us suppose that we are dealing with the longitude of the moon; we wish to construct a mathematical expression which shall so represent this quantity that we can calculate it for any given instant of time. The problem is really insoluble, and we cannot write down a complete expression for the longitude; but several different ways have been found of putting the solution into an infinite number of terms. Everything then depends on the consideration: Do these terms, as we take them one by one in the series, get rapidly smaller and smaller, so that although their number is really infinite, we can stop at a certain point in the confidence that no terms which come afterwards are large enough to be appreciable?

Within the last few years an apparently satisfactory answer to these questions has been found. From the enormous amount of work done on the problem during the nineteenth century three separate and considerably different ways of dealing with the Lunar Theory emerged; they are known by the names of Hansen, Delaunay, and Hill. The two former had after long trial been found insufficient. It remained to see what could be done with the later and considerably different theory devised

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by G. W. Hill. The enormous work of putting his mathematics into arithmetical form was undertaken by E. W. Brown, a Cambridge mathematician who became Professor of Mathematics at Haverford, U.S.A., and afterwards at Yale. After many years of unremitting labour his task was completed, and beyond question his tables of the moon's motion represent accurately how she moves according to the law of gravitation.

Apart from its importance in providing secure data for the Nautical Almanacs, a complete Lunar Theory enables one to examine one of the most fascinating of all scientific questions. Is Newton's law of gravitation rigorously true? In the absence of any sufficient physical explanation of the *cause* of gravitational attraction—which remains almost completely unknown—there is no convincing reason to be given why the attraction should vary exactly as the square of the distance between the attracting bodies. Instead of having distance to the power of two, might not the true law be distance to the power of (two + a very small quantity). This curious possibility has been examined several times, and always with a negative result; there seems to be every reason to believe that the simple square law is exact.

But on the other hand there is no longer any reason to doubt that gravitation alone is in-

FLUCTUATIONS IN MOON'S MOTION

competent to explain completely the observed motion of the moon.

Some fifty years ago the laborious researches of Newcomb made it clear that the moon never had, to that day, conformed to the programme devised for her by the lunar theorists; but then we had no solid assurance that the theory was without doubt complete. Now we have that assurance, and still our wayward satellite refuses to conform. At the end of the eighteenth century the moon was fourteen seconds of arc ahead; by the end of the nineteenth she was ten seconds behind her calculated place. "I regard these fluctuations," said Newcomb in his last paper on the subject, "as the most enigmatical phenomenon presented by the celestial motions." They have been recently explained to some extent by proof that the earth has three times in the last century experienced a very small sudden change in its rotation period.

The motion of the moon—or the accuracy of our knowledge of it—may be tested in another way which is full of interest, and which has of late years received much attention. Ancient historians and poets have recorded the occurrence of total eclipses of the sun—events so striking and awe-inspiring that they naturally made a profound effect on spectators and were inevitably associated with whatever important business might have been on hand at the time. In-

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deed, it is not a little remarkable how many decisive events seem to have been accompanied by eclipses of the sun, and this has even led to the suspicion that historians, writing long after the event, were tempted to embroider their narratives with any picturesque details that seemed appropriate. Such a suspicion does but add zest to an inquiry which has been pursued with great industry and remarkable success. The work of Cowell, Nevill, and Fotheringham has ranged over Babylonian, Assyrian, Greek, Egyptian, and Chinese records, and the complexity of the puzzles which these records presented has not altogether defied solution. It was found by Cowell that the tangle can be straightened out if we suppose that the length of the day is increasing at the rate of one-two-hundredth of a second per century! Its effect, gradually accumulating through centuries, is sufficient to bring into line with modern theory a whole series of eclipses of two thousand years ago.

There are several minute causes at work to affect the length of the day; but they do not all operate in the same direction. The continual deposit of meteoric dust must lengthen it; so must the friction of the tides. Shrinking due to cooling will shorten it, as will the gradual wearing down of the land by the action of ice and rain. But on the other hand the uplifting of the whole mass of the Himalayas within

CHANGE IN LENGTH OF DAY

times geologically recent must have lengthened it, and to a less degree the building of skyscrapers in New York is doing the same. On what side the balance of these opposing tendencies will lie cannot be predicted. Nor can we at present say what can be the cause of a sudden change in the length of the day. But if it has happened three times in the last century, it may have happened many times before, and that, it would seem, must discount the value of the researches on ancient eclipses.

There are other matters we must take into account, before we can say with certainty whether or no the moon and the planets move precisely according to the simple law of gravity. We must inquire, it is evident, whether any other forces than gravity can act upon those bodies in their orbits. What about friction? It is undoubtedly true that space is so very nearly empty as to offer scarcely any resistance at all to motion through it; but it is still uncertain whether there may not be some very slight effect of the kind. The instance which has been brought forward time and again is the retardation in the motion of the small comet known by the name of Encke—not because he discovered it, but because he investigated its motion, and found that its revolution round the sun was quickening—a paradoxical effect of resistance, which is easily demonstrated with a little mathe-

MOVEMENT UNDER THE LAWS OF GRAVITY

matical reasoning. The long researches of Backlund threw much light upon the problem, while showing at the same time that it is much more complex than had been supposed. By immense calculations, extending over many revolutions of the comet, he was able to show that the peculiar effect in the motion of this comet is not regular, but has been decreasing by fits and starts. For twenty years or so it will remain the same; then suddenly it will lose a quarter of its power; and again, after a lapse of years, another sudden change will take place. Most curious of all, these changes take place about the time when the sun is most affected with spots, and his general activities are most pronounced.

We have now to deal with the difficult question of Relativity, a word which is in everyone's mouth, but of which few can understand the mathematics. The extraordinary interest of the theory lies in the fact that by it the three co-ordinates of ordinary space and the time (but the time multiplied by the quite unreal quantity, the square root of -1) are interchangeable and indistinguishable, forming what is called a four-dimensional continuum. It is of course quite impossible to explain by any ordinary illustration what all this can mean; one must think of it as a kind of mathematical trick which produces some surprising results. There are three observed facts in astronomy

RELATIVITY

that are explained by the theory of relativity and not at present in any other way. One of these facts has long been known, that there is a certain movement in the position of the orbit of the planet Mercury for which the old laws of gravity cannot account. It is completely explained by the new theory. That was its first triumph. It then made two predictions: first, that rays of light passing near the sun would be bent by twice the amount by which they would be bent on a certain earlier theory; and second, that the lines in the spectrum of a star would be displaced by an amount depending upon the mass of the star.

The general theory of relativity was published by Einstein during the Great War, and for a long time only one copy of his memoir was available in England. That one copy fortunately fell into the hands of Sir Arthur Eddington, who perceived that in May 1919 there would be an excellent opportunity of verifying the first prediction. In that month the sun would be totally eclipsed along a track crossing Brazil and Central Africa, and it happened that the sun at the moment of eclipse would be placed in a field of stars brighter than the average, so that it might be possible to photograph them through the glare of the corona. Happily there was just time when the war was over for the Astronomer Royal to organize two British

MOVEMENT UNDER THE LAWS OF GRAVITY

eclipse expeditions, one to Brazil, and one to the island of Principe. The weather was not as kind as it should have been, but the results were sufficient to show that the stars were in fact displaced outwards from the sun by an amount which corresponded pretty closely with the theory of relativity and not at all well with the older theories. The result was confirmed at a succeeding eclipse, and was a striking proof that relativity was in some way or other true, however difficult it might be to understand it. Spectroscopists then turned to the second prediction, but found for a time a considerable difficulty in verifying it, since the effect they sought was small and the instrumental difficulties great. It was a good many years later that the second prediction had a sensational verification, on the discovery that the companion to Sirius must have a mass altogether out of proportion to its luminosity. This provided an unexpected opportunity of testing the second prediction, for the effect in the spectrum of the star would be very much greater than in the sun or in an ordinary star. The observation was possible only with the 100-inch reflector at Mount Wilson, and was difficult with that. But it was successfully achieved by Pease.

We can say then that although the theory of relativity appears to be a mathematical paradox, neglecting the distinction between space

PREDICTIONS OF RELATIVITY THEORY

and time which seems to us to be as real as anything in our comprehension, yet nevertheless it has explained one fact already known, and predicted two more which have since been verified. There must be some essential truth in it, and we may be well content to leave to mathematical philosophers the awkward question of its real significance. Much more lately it has made another prediction which seems to be in accordance with the observed facts, that the universe is expanding; but this we must leave till we consider what is the extent of the universe now known to us and what are the spiral nebulae. To deal with the difficult questions of what is meant by curvature of space, and how a four-dimensional space can be infinite in one sense and yet bounded in another, would be far beyond the scope of this book or the powers of its author.

But it does seem possible to say that the only motion in the solar system which could not be explained by the Newtonian theory of gravitation and which was triumphantly explained by Einstein's theory is the slow rotation of the orbit of Mercury. The rest of the planetary theory and the whole of the lunar seem to stand untouched. So the sympathetic concern for the repute of "Poor Newton" which was displayed in the first excitement of the Einstein affair was at least premature.

CHAPTER VI

THE DISTANCE OF THE SUN

A VERY important matter in any science is the numerical determination of the fundamental constants. A chemist is concerned for the accuracy of his atomic weights and specific heats, a physicist for his units of mass, of electricity, of light, and what not. In the same way the astronomer has to face continually the necessity for greater refinement in his determinations of the distance of the sun, of the masses of the planets and of the moon, of the aberration of light, the amounts of the various motions of the axis of the earth, and the velocity of the solar system in space.

As an example of such investigations we will take the determination of the distance of the sun from the earth, or its equivalent, the quantity known as the solar parallax; and we will select this for three reasons. It is the fundamental distance in terms of which all others may be expressed; its determination involves processes which are thoroughly characteristic of those operations of astronomy related to

DISTANCE BY SURVEY

measurement; and thirdly, a personal reason, the author in his youth spent ten pleasant years upon the problem, and feels for it a lively affection.

There are many ways of attack—some direct, others leading through a maze of by-paths in which one may always suspect ambush and surprise. We will deal first with the direct frontal attack, which is in principle simply a case of surveying upon a gigantic scale. The sun is an inaccessible point, but that is no fatal obstacle to finding its distance. The summit of Mount Everest was long considered inaccessible, yet its distance from Darjeeling was found with great accuracy.

Every surveyor knows that, if he wishes to get accurate results, his first care must be to lay out what are called "well conditioned" triangles, that is, triangles of which all the angles are moderate, neither too large nor too small; and of course the farther away an object is, and the smaller by comparison is the available base, the more difficult and uncertain is the resulting measurement. Now as our earth is but 8,000 miles in diameter, we cannot possibly have our base, from which to measure the sun's distance, more than 8,000 miles long, and practical considerations limit the distance to about 7,000. But the sun is more than 13,000 times this distance from the earth; and even if we were able

THE DISTANCE OF THE SUN

to select stations 7,000 miles apart, and observe simultaneously at each the angle between the sun and the other, our triangle would be hopelessly long and narrow, with the angle at the sun less than 15 seconds of arc. Moreover, the two ends of our base will be nearly on opposite sides of the earth, altogether invisible one from the other, and we must get over this difficulty by a roundabout process that greatly complicates the work, and makes it much less accurate. As a problem of pure surveying, the measurement of the sun's distance by direct settings upon the sun himself is quite hopeless, unless we are content with a probable error of two or three per cent. in our result.

The problem would be much simpler if we could see stars close to the sun. In that case it would not be necessary for us to be able to see from one end of the base to the other. Instead, we could make simultaneous observations of the position of the sun among the stars, which may be considered infinitely far away in comparison with the sun. When viewed from two different points, on nearly opposite sides of the earth, the sun would appear differently placed among the stars, by that small amount of 15 seconds of arc, invisible to the unaided sight though measurable with telescopes. This involves the true principle of all astronomical determinations of distance, that a near

TRANSITS OF VENUS

body is displaced with reference to more distant bodies, when observed from different points of view. In astronomical language, the nearer body has a parallax (Greek for a shift) relative to the distant bodies, and all such determinations are called determinations of parallax.

Though we cannot see stars close to the sun, we can, on rare occasions, see the planet Venus pass across the face of the sun as a small dark body; on which occasions Venus, being only at about one-third the distance of the sun, has a parallax relative to him. The consequence of this parallax is then that the time at which Venus appears to enter upon and to leave the sun, and the duration of the transit, depend upon the place on the earth which is chosen as a station from which to view the event. According as we select our station we may find an acceleration or retardation of about sixteen minutes in the moment when we observe a particular phase of the transit.

Historically, the transits of Venus have supplied the most famous occasions for the solution of our problem. The necessity of travelling to remote places invests the undertaking with an air of importance and adventure. It must have been something worth winning, to induce Governments to send large and well-found expeditions all over the earth, at a total cost of

THE DISTANCE OF THE SUN

many hundreds of thousands of pounds. Thus the solar parallax has among astronomical problems a dignity all its own, associated in public repute with the famous voyage of Captain Cook to the South Seas, and with the tremendous efforts put forth in 1874 and 1882. Unhappily, one must admit that the money spent in sending expeditions to Siberia, to the Pacific, to Kerguelen Island in the Antarctic Ocean, was practically thrown away, through no fault of the astronomers, unless indeed they can be blamed for failure to foresee the difficulty which wrecked the whole enterprise. They had gone to determine the exact instant at which Venus appeared in contact with the edge of the sun's disc. They expected to have a perfectly clear-cut view of this contact, and they did not at all anticipate what actually happened, that the atmosphere round the planet, filled with sunlight, blurred the sharpness of the phenomenon and left it uncertain within a large number of seconds at what instant the critical phase took place.

In transits of Venus we observe, not the parallax of the sun directly, but the difference of parallax between Venus and the sun; so that to complete our problem it is necessary to know what proportion the distance of Venus bears to the distance of the sun. But this involves no special difficulty. From Kepler's Third Law—

PARALLAX OF MINOR PLANETS

the squares of the periodic times are proportioned to the cubes of the major axes of the planetary orbits—we know the relative sizes of all the orbits with great accuracy. Find one, or the difference between two, in miles, and the rest is simple.

This principle gives us the key to all modern work on the solar parallax. Choose an exterior planet as the stepping-stone, and you have at once a great number of advantages. The planet is nearest and its parallax greatest when it is in opposition to the sun, visible all night, and observable consequently after sunset and before sunrise. The planet can be compared with the stars about it, so that the whole parallax, and not the difference between two, can be measured. And greatest advantage of all, the observations can be continued over weeks or months; failure at one moment can be repaired by success at others, and the astronomer is relieved of the disquieting anxiety lest a temporary breakdown in instrument or in weather should ruin everything at a critical moment.

The first modern application of this method was made by Sir David Gill, who had observed at Mauritius the Transit of Venus in 1874, and had made up his mind very definitely that little good would come of the transit of 1882. So in 1877, at a very favourable opposition and close approach of the planet Mars, he borrowed Lord

THE DISTANCE OF THE SUN

Lindsay's heliometer and established himself on the island of Ascension, near the equator. Every night the observing station in Mars Bay was carried some 7,000 miles by the rotation of the earth, and the planet thereby displaced among the stars by about 40 seconds of arc. Several months of successful work on the island, and a couple of years of severe calculation afterwards, produced the result of 93,080,000 miles for the mean distance of the sun. Then, as so often happens in scientific enterprises, when it was hoped that all was complete, some one suggested a possible flaw—the red colour of the planet might have produced a systematic error in the observations.

The next step was to try again, this time with three minor planets so small that they were indistinguishable in appearance from stars, and presumably free from the possibly damaging effect of that difference of colour which rendered the observation of Mars a little uncertain. The same courageous observer, by that time Her Majesty's Astronomer at the Cape, organized a co-operation between his observatory in the south and four in the northern hemisphere, to observe the small planets Victoria, Iris, and Sappho at their oppositions in 1888 and 1889. The labour was immense, the observations proving so accurate that they demanded the use in a great part of the work of eight-figure

INDIRECT METHODS

logarithms; but when the results were eventually published in two enormous red volumes of *Annals of the Cape Observatory*, it might well have seemed that observation had now done its uttermost to solve the problem. Nevertheless, within a few years the whole question was revived on a more extensive scale than ever.

To understand how this came about, and why it was necessary, we must look at some of the indirect ways of solving our problem. It will be worth our while to do so, even at the expense of a little difficulty, because they illustrate in a peculiarly interesting way how widely different branches of our science have delicate relationships with one another. There is an irregularity in the motion of the moon which depends upon the distance of the sun, though in a complicated way which we shall not attempt to follow. If this can by observation and calculation be disentangled from the many other irregularities which affect the motion of our satellite, then its value will serve to determine the solar parallax. Or again, the mass of the earth affects by its attraction the motion of the other planets, and they all affect one another by amounts depending upon the distances of the planets apart. If the action of the earth can be disentangled from the others, the mass of the earth can be found, and thence, by a process much too difficult to

THE DISTANCE OF THE SUN

describe here, we have another value for the distance of the sun. Or again, the motion of the earth about the sun, combined with the velocity of light, produces the well-known effect of the Aberration of Light, which causes all the stars to move apparently in little ellipses each year. The size of the effect can be measured; the velocity of light can be measured independently in the laboratory; and from the two results we may deduce the velocity of the earth in its orbit. Then, knowing the length of the year, it becomes a simple matter to find the size of the orbit, and the distance of the sun.

These three are typical, and the most important, of the indirect methods of finding the quantity of which we are in search. Opinions will always be divided upon the question, how far any of the indirect results should be preferred to the direct results of measurement; and it is probable that those who have made the direct measurements will be the least willing to attach an exaggerated value to the indirect. But it cannot be denied that when the results failed to agree it produced an awkward feeling that all was not well, which was intensified when all the indirect methods appear to conspire against the result given by the direct. Such a crisis occurred about the year 1898. The indirect results combined at that time to make

PLANET EROS

the distance of the sun several hundred thousand miles greater than direct measurement would allow, from which arose a renewal of interest and a general anxiety about the great problem.

At this moment a happy accident occurred. In Berlin there was a society which maintained a small observatory where non-professional astronomers might find an equipment beyond their private means. With the photographic telescope of this observatory Dr. Gustav Witt was engaged in a search for certain minor planets which had been neglected and had become lost. With the good luck which often rewards good work, he found a prize far exceeding in value that at which he aimed—a minor planet indeed, but moving in a path remarkably situated, very eccentric, and bringing the planet on rare occasions within 15,000,000 miles of the earth. So soon as a first rough approximation to the path of the new planet had been calculated, the great value of the discovery was apparent: it provided an opportunity of determining the distance of the sun with an accuracy much greater than had been possible before. The opportunity, it is true, would occur but rarely, and the most favourable possible occasion had just been missed, having occurred four years before the discovery. But in the autumn and winter of

THE DISTANCE OF THE SUN

1900—01 a quite satisfactory opposition of the planet was to occur, and it became immediately a pressing matter to ensure the necessary co-operation between astronomers. Here again fortune was kind.

Throughout Europe the skies of that winter were very unfavourable. At Cambridge the author had the pleasure of being on duty with the photographic telescope from dusk till dawn for nearly three months, during which time only five or six nights were more or less clear throughout. Had visual observations alone been possible, one could scarcely, in those brief and broken intervals of clear sky, have obtained a sufficiency of measures. But the photographic plate, in work of this kind, is so much more expeditious that it was possible to obtain at Cambridge alone about five hundred photographs, on which the position of the planet among the stars could be measured with great precision. Many other observatories obtained as much material; a few, happily situated in fine climates, obtained much more; while the visual observers had been equally active and had accumulated an enormous mass of measures, referring the planet to great numbers of faint stars whose positions at the time were entirely unknown.

Here, then, was an overwhelming richness of raw material for the solution of the problem.

EROS PARALLAX CAMPAIGN

How to deal with it economically and effectually became a question of the highest interest. The author will always be grateful for the happy combination of circumstances which resulted in the whole final discussion being placed in his hands, with the means necessary to secure help in the calculations.

In an enterprise of this kind, which must necessarily take some years to complete, the unkindest thing that can happen is for all to go smoothly; for calculation is apt to be tedious and requires enlivenment. The fascination of the work lies in the solution of the puzzles which hardly ever fail to present themselves. On the occasion of which we speak there was no lack of this sporting element. It was the first time there had been the opportunity on a grand scale of comparing minutely the results turned out by different photographic telescopes, and by different ways of measuring the plates and reducing the measures to a common form. Naturally enough, when one searched deep one found discordances and disagreements of small amount, but of amount which could not for a moment be neglected. One had to try all kinds of experiments to discover what was wrong with photographic object glasses; to find out why one calculated prediction of the planet's path did not accord with another, though both were built upon the same foundations. One had to

THE DISTANCE OF THE SUN

maintain correspondence with observatories all over the world, leading to the formation of many valued friendships; and one had continually to steer in a narrow channel between dangers on either hand, each offering the chance of shipwreck. On the one hand there was the danger of neglecting some minute precaution against error which might affect the whole result. On the other hand there was the danger that pursuit of the tempting inquiries presenting themselves at every turn might so prolong the work that it would never get finished.

Some one has laid down the principle that it is a mistake to plan work which will take longer than ten years to complete. Judged by their standard the solar parallax determination from the planet Eros just escaped censure. It was begun in the Paris Congress of 1900, and it was practically finished when the final results were communicated in brief to the Académie des Sciences in 1910. Whatever judgment may be passed in the end upon the results of that enterprise, they presented at the time two features which were eminently satisfactory; the photographic and the visual observations gave the same result; and that result was nearly the same as the previous result made by direct measurement.

Nearly at the same time a beautiful piece of

THE SOLAR PARALLAX

work came from the Cape Observatory—a determination of the distance of the sun from spectroscopic observations, long anticipated, but only achieved after great efforts at conquering instrumental difficulties. The spectroscope is able to measure the velocity in the line of sight between the earth and a star. This velocity necessarily varies with the season of the year, and the variable part due to the motion of the earth round the sun can be disentangled from the constant part due to the combined velocities of our sun and of the star in space. Hence one finds the ratio between the velocity of the earth and the velocity of light—that is to say one finds the constant of aberration by a new and direct method; and the well-known values for the velocity of light and the length of the year give us eventually the distance of the sun, which by this new and quite independent method came out in almost precise agreement with the old.

The result which emerged from that Eros campaign was expressed in four figures:—

Solar Parallax from Eros = $8''.806$.

For the moment one is left wondering how this can be called a determination of the sun's distance. The fact is that the astronomer does not want the distance of the sun expressed in miles; for his purposes the numbers are inconveniently

THE DISTANCE OF THE SUN

big and the whole thing in the wrong shape. What he really cares about is the ratio between the equatorial radius of the earth and the mean distance of the earth from the sun. This small quantity is the sine of a certain angle; the angle is what we ordinarily call the Solar Parallax, and it is independent of any reference to miles or kilometres. These units, more or less arbitrarily defined by standard bars of platinum, are indeed purely mundane, and have no real place in celestial measurements. One may very well question how far it is desirable to use them for celestial distances, though there is no difficulty in doing so if it is wished. Geodesy has measured the radius of the earth's equator, and makes it about 6,378 kilometres. Using this value we find at once from the above value for the solar parallax that the mean distance of the sun from the earth is 149,400,000 kilometres, or 92,830,000 miles.

An interesting by-product of the investigation was a value for the mass of the moon in terms of that of the earth. This quantity became involved in our problem in the following way, which illustrates very clearly the complexity of measurements made from a moving earth. We have been speaking of observing the planet Eros night and morning at a single observatory, or more or less simultaneously at two observatories far apart upon the earth's surface—Greenwich

MASS OF THE MOON

and the Lick Observatory for example, and for simplicity we have spoken of the displacement of the planet among the stars, as thus viewed from different points, as though it were the only displacement that the planet suffered. But, in fact, the planet is moving all the while in its own path round the sun, and so is the earth; while the motion of the earth is complicated by the fact that the earth has a partner, the moon. They turn about one another in their progress much as a heavy man waltzing with a little girl progresses round a ballroom, the light partner turning in a larger circle, the heavy in a smaller. In the case of the earth and the moon the one is so much heavier than the other that the common centre of gravity about which they turn is within the surface of the earth, though far from the centre; but the effect of this monthly oscillation of the earth is to produce a monthly irregularity in the apparent motion of any planet viewed from its surface. Disentangle this monthly oscillation in the place of the planet, determine its amount, and one can deduce the size of the oscillation in the earth's motion which produces it. Thence one derives the proportion between this displacement and the distance of the moon, and from that proportion the mass of the moon in terms of the earth. The observations of Eros gave for this proportion 1 : 81.5.

THE DISTANCE OF THE SUN

These close approaches of the planet Eros occur at regular intervals. We have seen how almost the best possible opportunity was missed in 1894 because the planet was not discovered until 1898, but that the winter of 1900-01 fortunately provided a fairly favourable opportunity that we have discussed at some length. In that winter the planet was far north and unobservable in the southern hemisphere. Since then there was no favourable opportunity until 1930-31, when the planet came a good deal nearer than it did thirty years before, and this time was, at its nearest, travelling rapidly south, so that it came within the reach of the Royal Observatory at the Cape of Good Hope. Another great campaign of observation was organized, and another great mass of material was obtained, which is at the time of writing being discussed at Greenwich under the direction of the Astronomer Royal.

During the nineteenth century the different methods of obtaining the distance of the sun gave remarkably discordant results, and one expected that each new determination would absolutely contradict the last. During the present century, on the contrary, several independent determinations have very happily supported the result which came from the planet Eros, and one felt that the value was stabilized. It will be of the highest interest to see when the results of

SECOND EROS CAMPAIGN

the last campaign are published a few years hence whether this stability is maintained or whether we are launched into a new sea of troubles.

CHAPTER VII

THE STARS

THE Ancients, says Fontenelle, were pleasant Gentlemen, to imagine that the celestial Bodies were in their own nature unchangeable, because they observed no change in them. In modern astronomy the stars have individualities: we know them as near or distant; having large or small velocities among their neighbours; surpassingly brilliant of surface or relatively dull; single, or double to the telescopic sight, or double only to the searching scrutiny of the spectroscope; steadfast in light, or variable by eclipse, or by causes yet undetermined; maintaining their radiation by losing mass; but destined to eventual decay. With individuality they lose their name of fixed stars. No longer can they be regarded as the unchanging background before which the sun and the moon and the planets move: mere useful points like the beacons of a survey. We are not, and never shall be, in a position to neglect this aspect of the stars, expressed in the word "fundamental," but the funda-

EARLY CATALOGUES

mental star catalogue no longer appeals to us as the last word in stellar astronomy. We may think of the stars as mere points in space, and be interested in their positions, their distances, and their proper motions—or we may think of them as suns, having different compositions, different masses, and all kinds of different physical properties. The first is astronomy in its restricted sense; the second is the modern subject of astrophysics.

To begin with astronomy proper—the science of star places and apparent motion, often called astronomy of position. Its foundations were laid, it is believed, by Hipparchus more than a century before Christ. His catalogue has not come down to us under his name, but there are good reasons for thinking that Ptolemy's famous catalogue in the *Almagest* is founded upon an earlier catalogue of Hipparchus. Right well, in that case, does Hipparchus deserve the name of founder of practical astronomy, for no sensible improvement on that catalogue was made until the days of Ulugh Beigh, who reigned at Samarcand, founded a great college and observatory, and made a revision of Ptolemy's catalogue which is dated 1437. Tycho Brahe's star catalogue, made with the greatly improved instruments of his observatory at Uraniborg, was published in 1602, the first of many famous catalogues

THE STARS

that have come from round about the Baltic. Then we come to the invention of the telescope, and its application to measurement as well as to description; to the names of Flamsteed and Bradley, Lacaille and Lalande, Mayer, Piazzzi, and Bessel. By their labours was reared the substructure on which in a sense the whole modern astronomy of position is carried.

The brightest stars have ancient names, some of them from the Greek, as Procyon, or Latin, as Castor and Regulus, but more from the Arabic, as Aldebaran, Altair, and Algol (the Demon); and the stars are by old practice arranged in districts of the sky as constellations, of which those visible in the ancient world have fanciful generally Latinized names derived from legend and myth, as Perseus, Andromeda, Gemini, Argo; or from some rather remote resemblance to the shape of heroes, as Orion and Hercules, and of animals, as Ursa, Taurus, Aries, Capricornus, Leo; while the more southern constellations have names obviously manufactured, as Mensa and Octans and Pictor.

The boundaries of the constellations, for long exasperatingly vague and indeterminate, have recently been laid down in segments of meridians and parallels by international agreement.

Within the constellations the stars have

NAMES AND NUMBERS

long been denoted by Greek letters Alpha, Beta, Gamma, . . . more or less but not strictly in order of brightness; thus Alpha Canis Majoris is Sirius, Alpha Lyræ is Vega, and Beta Orionis is Rigel, and there is a tendency to drop all but the most familiar names in favour of the Greek letters. Then when the Greek letters run out there are certain numbers from Flamsteed's catalogue surviving for particular stars, as 61 Cygni, 70 Ophiuchi, though no one ever hears now of 60 Cygni or 71 Ophiuchi. This about provides for the naked eye stars. For those a little fainter there are the numbers in famous early catalogues of Lalande, Piazzzi, Groombridge. The stars down to about the ninth magnitude are generally known by their zone numbers in the B.D. (Bonner Durchmusterung) of Argelander, or farther south by the numbers in the zones observed and plotted by Gould at Cordoba. Variable stars are lettered from R to Z and then by double letters RA, RB, . . . with the constellation names; double stars by their numbers in the catalogues of Struve, Burnham, Aitken, and Innes. For the fainter stars there is nothing for it in general but to give their positions; but when a very faint star is remarkable for any reason it has become a recent habit to call it, like a comet, by the name of its discoverer: Barnard's star with a very large proper motion; Pearce's

THE STARS

and Plaskett's stars, the most massive known; or van Maanen's star, a white dwarf. In this variety of method there is little system but a great convenience, and a number which has become historic, such as 61 Cygni, will survive when adjacent numbers of some catalogue or other are discarded.

Accurate places of the stars are essential to the useful applications of astronomy—the determination of time, navigation, surveying. Secondly, accurate places of the stars are required as reference points, to which the sun and moon, planets and comets, are all referred. Without good star places we can have no theory of the motions in the solar system, no orbits of planets or of comets. And thirdly, without accurate catalogues of the stars we can know little of the motion of our sun among the stars, or of the stars among themselves.

When one compares a catalogue of to-day with a catalogue made a hundred years ago, one finds differences between the places of stars now and then. Some of these are due to nothing but errors of observation in one catalogue or in both. We have means of estimating how large these errors are likely to be, and can say approximately what the average accidental discordance should amount to. When we find a great number of observed differences much greater than these, we must recognize that

PROPER MOTIONS

the stars are not fixed; that some, on the contrary, have motions proper to themselves which become quite evident in the course of fifty or a hundred years. A most important purpose of star cataloguing is to determine the magnitude and direction on the celestial sphere of these proper motions of the stars.

Now it is practically impossible to observe with the meridian circle—the instrument used for fundamental star cataloguing—stars fainter than magnitude nine and a half; while the number of stars down to that limit is already so large that it has been found impossible to deal with more than a selection of them. For the places of stars fainter than this, we must rely on measurements made on photographs. But a photograph will not determine the absolute places of stars, as the meridian circle can. We can fit each plate on to the celestial sphere by means of the few intermediate stars whose relations to the fundamental stars are more or less imperfectly known; or on the other hand we may fit two plates of the same area at different dates together directly by the large number of faint stars, so as to discover any proper motions in the interval. A store of photographic negatives, such as those made for the great Astrographic Chart, becomes thus of increasing value with the passage of years. And negatives made at

THE STARS

Cambridge in 1900 for the parallax of Eros were used thirty years later for detecting the proper motions of stars fainter than could ever be catalogued with the meridian circle.

Having determined a great number of proper motions we have next to inquire whether they show any significant arrangement. Suppose for the time being that the real motions of the stars are haphazard, distributed according to the laws of chance with which mathematics can deal. Then, if the sun is at rest, the proper motions of the stars, as we see them, will be haphazard also, and there are definite tests which can be applied to see how nearly haphazard the motions are. But if the sun is not at rest, his movement will introduce at once a certain degree of order into the otherwise random proper motions. The nearer stars on either hand will have a general tendency to move backwards, that is to say, to appear to do so; they will, in fact, on the average, be left behind, while the stars in the part of the sky to which the sun's motion is directed will be very little or not at all affected; and so will the stars in the opposite quarter of the sky. Working upon this principle, many astronomers made discussions of observed proper motions, with a view to finding the point

STAR STREAMING

towards which the sun is moving: the "apex of the sun's way."

Different selections of stars gave somewhat different values for the position of the apex, but there is a general consensus of result that the motion of the sun is directed towards the constellation Lyra, or at any rate towards that region of the sky.

At first there was no suspicion that the basis of this investigation might be unsound, because of the implicit assumption that the real motions of the stars are random. Then in 1904 Kapteyn, of Groningen in Holland, upset many of our previous notions. He had been engaged for many years on a series of intricate researches into the arrangement and the motions of the stars in the universe. He had prepared an elaborate machinery of theory and calculation which would work if the stars were moving at random, and would not work if they were not. On arriving at the crucial point, where theory was confronted with observation, the machine would not work, and its manner of breakdown showed at once what was wrong. The stars under discussion were found to be moving in two streams, crossing through one another and pretty well mixed, but with an average velocity so considerable that it destroyed any possibility of treating the motions of the stars at random.

THE STARS

For twenty years after Kapteyn's announcement the subject of star-streaming exercised the ingenuity of mathematicians and computers, in the then belief that our sun is somewhere near the centre of our great system of stars. It took on a different aspect when the sun's place was found to be far away towards the borders of the Galaxy. If star-streaming has rather faded out of interest in recent years, it is because it is now seen to be an incident in a much larger affair, the rotation of the Galaxy about a distant massive centre, which will be dealt with in Chapter IX.

The greatest impediment to the study of star distribution is the extreme difficulty of determining a star's distance from the sun. The principle is easy: the nearer stars should appear to oscillate in a yearly period, as the earth moves round the sun; the range of the oscillation should give the distance of the star. The practical difficulties of turning this simple principle to account are due to the immense distances of even the nearer stars, which make the oscillations infinitesimal. Measurements for the direct determination of a star's distance are generally made nowadays upon a photographic plate, taken with a telescope of considerable focal length, so that the plates are on a large scale. If a telescope of focal length forty feet were photographing the star which is nearest

STELLAR PARALLAX

the sun, the star-image would in the course of the year oscillate two thousandths of an inch on each side of its mean place; this is all the effect produced by the displacement of the earth across the 186,000,000 miles which is the diameter of the earth's orbit. And this is for the very nearest star. Very few stars—perhaps two or three hundred in the whole sky—are within ten times its distance; very few stars, then, will be displaced on the plate a five-thousandth of an inch either way by the earth's revolution in a year. Their distances are so great that only some thousands of stars are within the range of possibility, while the great bulk of the stars in the sky are utterly beyond the reach of this direct geometrical measurement.

It was thought at one time that a rough estimate of a star's distance might be deduced from its brightness; but it was soon found that most of the bright stars are quite out of reach; some few of the faint ones are among the sun's nearer neighbours. Hence, though no doubt it is true that on the whole the fainter stars are the more distant, for any particular star or star group its brightness tells us little about its distance. The criterion of nearness is proper motion. If a star has a large proper motion there is some chance that it is within measurable distance; so that stars with large proper motions get selected for measurement. But it is

THE STARS

evident that another star without proper motion may be just as near, and will escape observation because there is no reason to select it as promising some return for a great deal of work. This is doubly unfortunate, because it gives to statistics of stellar distances a bias which can scarcely be avoided.

Only a very small part of the stars, then, can have their distances determined by direct survey. And the stars vary so much in intrinsic brilliance that their apparent brilliance is little indication of their distances. But if there were some independent way of estimating their real brilliance, comparison with the apparent brilliance would at once give the distance. The confidence with which astronomers now speak of distances a hundred thousand times as great as the limit of the above method is based on the fact that the average if not the individual real brilliance of whole categories of objects can now be estimated. But it will be more convenient to defer this matter to Chapter VIII.

Many have tried to find some way of picturing the distances which separate star from star in the sun's neighbourhood. Perhaps there is no way better than to imagine a model in which the sun is represented by a grain of sand one-hundredth of an inch in diameter, and the earth by a quite invisible speck one inch away. Upon this scale the nearest star

DISTANCE AND DISTRIBUTION

will be another grain of sand some four miles away, and the other stars will be scattered at somewhat greater distances apart. To this incredible sparseness are the stars reduced when we try to look at them in three dimensions.

While the model is in mind, let us mention a result of spectroscopic work which gives us the velocity of the sun with reference to his neighbours—four radii of the earth's orbit per year, or four inches on our model. At this rate the sun would take some seventy thousand years to reach his nearest neighbour. Now so far as is known we have no real reason for assuming that the stars are gathered anywhere much more closely than this, except in the star clusters. We shall do well, therefore, to view with scepticism any theories which require crowding or collision among the stars. Despite the richness of the sky, the emptiness of space is its most striking character.

In the first edition of this book the word "magnitude" was used from time to time to denote brightness of a star, but there was no explanation of the scale of magnitudes, nor any indication how they were measured. Magnitudes then were convenient in describing a star, but they had nothing of the importance they have now when we use them for measuring distance.

The ancients divided the visible stars into six

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classes of brightness, and when in the nineteenth century astronomers began to measure the light of the stars scientifically, they found that the arbitrary scale of the ancients corresponded fairly well to the law that the eye appreciates not an arithmetical but a geometrical progression in the light of a star. The least difference appreciable is a percentage, not a fixed quantity. It was found further that the ratio corresponding to the ancient's scale was $2\frac{1}{2}$ to 1, that is to say that an average star of the fourth class was $2\frac{1}{2}$ times as bright as one of the fifth; and that this ratio was fairly well preserved in the old classification, naturally, because it corresponded to a physiological law. Now in dealing with numbers that increase in this geometrical progression it is necessary to use logarithms, and convenient to have the logarithm of the constant ratio a figure easy to remember. It was remarked that the logarithm of the number 2.512 was the easily remembered quantity 0.4000, and this led to choosing 2.512 instead of 2.500 as the ratio between one magnitude and the next in a scale of measured brightnesses, and to extend it of course down to the faintest telescopic stars.

Measuring the brightness of a star is an uncertain business. First, they tried to find at what point of a tinted glass wedge the star was extinguished, and found all sorts of

STELLAR MAGNITUDES

troubles with after images upon the retina, like the green spots which float before one after looking too long at the sun. Then they tried using other ways to equalize the star with a standard star, natural or artificial, and found that the relative brightness of two objects as judged by the eye depended upon their relative positions, the retina being more sensitive in some directions than in others. The best results were obtained with a rather elaborate apparatus involving polarizing prisms to reduce the light of the Pole Star to that of the star under measurement. And then there began to be doubts as to whether the Pole Star itself was not variable, as indeed it proved to be. Alternatively, one naturally tried measuring the diameters of the star images upon photographic plates, not strictly logically, because theoretically the photographic images of all stars ought to be the same size, but some denser than others according to their brightness; whereas in fact the imperfections of the objective and the unsteadiness of the image on ordinary nights, added to the creep of the photographic image from one molecule of silver bromide to another, make the images of bright stars larger than of faint. It would indeed be very inconvenient if they were not. The law of increase cannot be predicted, it must be determined experimentally; the natural thing to do is to take a

THE STARS

series of exposures each 2.512 times as long as the one before, but it was soon found that this did not give a scale of photographic magnitude which agreed with the visual. The subject is full of difficulty and an immense amount of work has been spent upon it by which we now have a pretty good scale both visual and photographic. The difference between the visual and photographic magnitude of a star, being an index of the star's colour, is a valuable criterion that is useful in such problems as the absorption of light in space.

We have only begun to realize how happy was the choice of our magnitude scale since we have had to deal with the immense distances of recent years. If you go down from one magnitude to the next by a factor 2.512 , a difference of 5 magnitudes evidently correspond to a difference in light of 2.512 to the power of 5; a nasty number to calculate without logarithms but easy enough with, since five times 0.4 is 2, and 2 is precisely the logarithm of 100. Since the apparent brightness of a star diminishes as the square of its distance increases, it has only to be removed 10 times as far away to have its apparent brightness reduced to 100th, or to lose 5 magnitudes. We have thus the excessively convenient scale, 10 times the distance means 5 magnitudes, whence 10,000 times the distance means 20 magnitudes. Suppose

SCALE OF MAGNITUDES

then that a star of magnitude 19, about on the limit that can be photographed by the 100-inch telescope, were brought to a distance of only one ten-thousandth of its present distance, it would be 20 magnitudes brighter; that is to say its magnitude would be 19 minus 20, or minus 1. We need not be disturbed that the scale has run beyond zero in the negative quantities, for we are already familiar with Sirius, so much brighter than the average run of first magnitude stars that its magnitude is -1.4 . This rule is the most convenient thing in the world for the mental arithmetic which is wanted in reading nowadays about the universe, and teaches us to think in geometrical progression. To lose 5 magnitudes in going 10 times as far away seems a great deal; to lose only 20 in going 10,000 times as far away looks nothing like so serious.

When the relative scale of magnitudes was settled, it became necessary to adopt a zero, and this needed some consideration of the units suitable for expressing the distances of the stars. Distances in the solar system are conveniently measured in terms of the mean distance of the earth from the sun, and that distance is of course the half-base upon which the distances of the nearer stars are geometrically determined. A star which has a parallax of one second of arc, that is to say a star at which

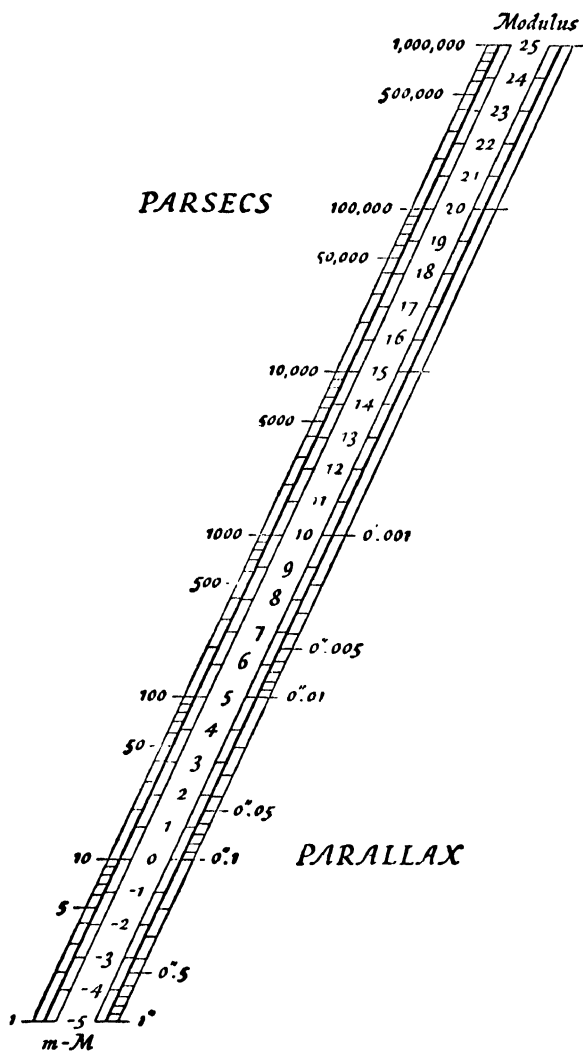
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the radius of the earth's orbit is some 93,000,000 miles subtends only one second of arc, is 206,265 times as far from the sun as the earth is. No star has hitherto been found so near; the unit is thus inconveniently small, and the distances of the stars were until recently generally expressed by their parallax. This was not only illogical, to express a distance by an angle, but it was also inconvenient because as the distances got greater, the angles got smaller, while the magnitudes got greater. It was proposed then some 20 years ago, probably by Turner of Oxford, to take the distance of a star whose parallax is one second of arc as a unit and to call that unit of length a parsec, one of those manufactured words which were less common then than they are now. There was an alternative unit in use, the light year, meaning the distance which light travels in a year at the speed of 186,000 miles a second; but this unit was also illogical; to express a distance in time was no better than to express it as an angle, and the light year had no simple relation to the magnitude. Hence the word parsec, rather derided when it was first proposed, has become not only established, but a very real convenience, and when distances in parsecs become too big we express them in kiloparsecs or in megaparsecs, which will seem natural enough to radio enthusiasts accustomed to talk of kilo-

ABSOLUTE MAGNITUDES

cycles and megohms. Only one step more was necessary to define our scale, and there has been little difficulty in agreeing that the standard of magnitude shall be a star whose apparent magnitude is zero at a distance of 10 parsecs, and that what is called the absolute magnitude of any star shall be the apparent magnitude that a star would have if it were set at that distance. On this scale our sun, which has an apparent magnitude of -26.7 has an absolute magnitude of 4.8 , but upon this scale there are some stars of such surpassing brilliance that their absolute magnitudes are -5 and -6 . The great simplicity of this system is best shown by the diagram on page 160, which we have chosen to be the one diagram in a book which in accordance with precedent has only one diagram.

There remains for definition one term which has been introduced to astronomy of recent years: the modulus. The absolute magnitude of a star is the magnitude the star would have if it were at a distance 10 parsecs. The difference between this absolute magnitude and its apparent magnitude, which represents its apparent brightness in the sky, and which we can measure by various means, is the modulus, which is a measure of its distance. For example, we see from the diagram that if a star has a modulus of 15 its distance is 10,000 parsecs.



ABSOLUTE MAGNITUDES

There are several ways of judging the intrinsic, the absolute magnitude of a star. The first is by comparing the relative intensity of certain groups of lines in the star's spectrum. Some 25 years ago it was first observed that these relative intensities vary from star to star, and that for the relatively few cases in which the distance of the star could be determined by survey, and its absolute magnitude thus obtained from its apparent magnitude, the relation between the intensities of these groups of lines was closely related to the absolute magnitude. Having thus standardized a scale, it was possible to apply that scale to the spectra of other stars, too far away to be measurable by the geometric method. Indeed there was a particular merit in this method that its applicability is independent of the distance of the star, at least to a great extent, though it does require that the star should be bright enough to give a spectrum of fine detail. That at first limited the method to the brighter stars, but this difficulty has been diminished by the construction of better telescopes. The method has, however, one serious disability, that it is not applicable to the whiter and bluer stars, merely because the necessary groups of lines do not appear in their spectra; and it is just these bright but rather distant blue stars whose distances one would especially like to

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know. For the time being progress in that direction seems to be barred.

A much more powerful method of obtaining the absolute magnitude of stars of a certain class has however become the most useful and widely-used tool in modern astronomy. It is based on a peculiar property of certain variable stars, that their periods are closely related to their luminosities. But the history of this discovery, and its method of application, belong to the following chapter.

It has long been known that many of the stars are variable in brightness. The longer the period of a variable star, the less it is disposed to follow regular laws; the shorter the period, the more precisely does the star repeat, time after time, its fluctuations in light. There are classes of stars which increase quickly and diminish slowly; others, less numerous, which do the reverse. Some have irregularities during the ascent, some during the descent. Some have double, unequal maxima, separated by equal minima. Some have prolonged maxima, and minima quickly passed; in others the minimum is prolonged, and the maximum no sooner reached than the light begins again to decline.

Of these classes there is one much more important than the others, the Cepheid variables, named after Delta Cephei the most conspicuous,

ALGOL VARIABLES

and including the variables in the globular clusters. They vary very regularly, rising suddenly and falling more slowly, in short periods, and to them we shall presently return.

There is only one kind of variable star that is certainly and completely explained—the Algol-type of eclipsing variable, named from the bright star Algol in Perseus which was first remarked and has been most completely studied. In this type the star is normally at full brightness—at regular intervals its brightness fails and quickly recovers. It is now fully established that this is due to an eclipse. The star has a dark companion revolving round it, like a gigantic planet, very close. The plane of the companion's orbit is so placed that our sun lies nearly upon it, from which the consequence follows that at each revolution the star is partially eclipsed.

Algol was the first member of that class which has now become enormously important under the name Spectroscopic Binaries. A binary star is a double star in which the components are observed to revolve about their common centre of gravity. We shall deal presently with the cases in which both stars can be seen in the telescope. A spectroscopic binary is a star which under the highest telescopic power remains single, but which with the spectroscope is proved to be a pair of stars in revolution. To

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this, which used to seem the most remarkable of all the doings of the spectroscope, we must devote a brief explanation.

The position in the spectrum of any line, bright or dark, depends upon the number per second of the corresponding waves of light which enter the spectroscope. If the star and the spectroscope are approaching one another, the number of the waves of light from the star which the spectroscope meets is naturally increased; if the star is receding, the number is diminished. It follows from this that if a star is alternately advancing and receding, the lines in its spectrum are shifted alternately towards the violet and the red ends of the spectrum. The shift can be measured and the measurement can be translated into the statement that the star's velocity is variable by so many miles per second.

In the Algol pair the companion is dark, or at least gives very little light compared with Algol itself. But this is not always so. Often both stars of a spectroscope binary are nearly of the same brightness. Then the spectrum belonging to the one is shifted towards the violet while the spectrum of the other is shifted towards the red; in this case all the lines in the compound spectrum belonging to both components are alternately double and single.

SPECTROSCOPIC BINARIES

A surprising degree of success has rewarded the search for variable velocities. One star out of every four or five examined proves to be a spectroscopic binary, and the proportion seems to grow steadily larger as the appliances grow year by year more powerful and more delicate.

The large proportion of spectroscopic binaries among the stars is a triumphant vindication of the mathematicians, who have shown how easily an elastic globe of gas, like a star, may become unstable, and after passing through a sequence of changes become of a pear-shaped figure which is preliminary to separation into two parts. From the mathematical analysis of the problem this ought to happen sometimes; observation has now shown that it happens very frequently—once out of three or four times, perhaps. From another point of view the discovery of so many spectroscopic binaries disturbs the idea, drawn from our own solar system, that the function of a star is to nourish with heat and light a family of planets. The terrible problem of the motion of a planet round a pair of suns has not yet been solved, but it seems quite unlikely that such a planet could pursue an equable way conducive to the development of life upon its surface.

The same method which allows us to detect variability in the motion of a star allows us to

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measure the velocity, whether variable or not, with which that star is approaching or receding from the sun; while, when enough of these velocities have been determined, we may derive at once the direction and the velocity of the sun's motion in space. Other methods gave the direction, but were not powerful to show the velocity. The spectroscope possesses what the other methods lacked, and makes it evident that the sun, with all the planets, is moving with a speed of some twelve miles a second towards the neighbourhood of the constellation Lyra.

Now to return to those binary stars which are visibly binary, and which can be measured and studied by the telescope without the aid of the spectroscope. When it was first shown that such pairs obeyed the laws of gravitation in their motions, it seemed a great thing to have proved that those laws were no local regulations of the solar system, but had universal force. Now that the spectroscope has shown that the most distant stars are formed of very much the same materials as the sun and the earth, we should find it strange if they were not subject to the same laws of gravitation. When irregularities of motion exist, they can be explained very plausibly as due to the disturbing action of some third, invisible body.

BINARY STARS

The measurement and calculation of binary stars is a relatively simple matter, requiring a good telescope without over elaborate accessories, but requiring above all a perfect eye and delicate hand for its successful prosecution.

The very close pairs, which demand large telescopes for their observation, demand also very frequent observation, for many of them are in rapid motion, completing their revolutions in relatively few years. The wider pairs, which are easier to measure, are less likely to be in rapid motion, but must not on that account be neglected.

The amount of matter in a star, which by the law of gravitation attracts and is attracted by all the other matter in the Universe, may be called its mass or its weight, provided we remember that mass is independent of position or surroundings, while weight is not. The term mass is more generally used, but weight is employed in a recent famous book.

In general we can determine directly the mass of stars only when they are binary. By Kepler's third law the combined mass of the two components in terms of the sun's mass, multiplied by the square of the periodic time, is proportional to the cube of the orbit's semi-axis major. Measures of the distance and position angle of a binary star, continued throughout its revolution, give the period and the major

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axis in angular measure, which can be converted to linear measure when we know the distance of the pair; and from the above relation we may deduce the combined mass of the pair relative to the mass of the sun. The necessity of knowing the parallax limits this method, but a visual binary star is usually not very distant, or it would not be visibly double, and it will probably have a measurable parallax.

If the parallax is large the motion of either component about the common centre of gravity will introduce a periodic term into its proper motion from which the relative sizes of the two orbits may be determined, and the combined mass portioned between the two, as has been done for Sirius and some other stars. For Sirius the periodic term in the proper motion was detected by Bessel long before the faint companion was first seen by Alvan Clark in 1862. The masses of its components determined in this way are 2.45 and 0.85 that of the sun. For the binary Alpha Centauri the two masses are 1.4 and 0.97; for Procyon 1.24 and 0.39; and for the faint red star Krüger 60 the masses are 0.25 and 0.20, a fourth and a fifth of the sun, and the smallest masses certainly determined.

When the star is not visually double, but the spectroscope shows that its velocity is regularly variable, and can be interpreted as due to revolution round the common centre of gravity

MASSES OF BINARIES

of itself and a fainter companion, some elements of the orbit can be determined, but not others; we can for example find the period but not the inclination of the plane of the orbit to the line of sight, but we do know the projected velocity in linear instead of in angular measure, and consequently we can determine the combined mass reduced by a factor less than unity depending upon the unknown inclination: that is to say, we can determine the lower limit of the mass. Moreover, if both components of the star are bright enough we can see both spectra, work them up independently, and obtain the ratio of the two masses.

By this method it can be shown, for example, that Capella is a binary star with a period of 104 days, and the masses of its components are at least 1.19 and 0.94 that of the sun. How much more depends upon the inclination, which affects both numbers in the same proportion, so that the ratio of the masses, 1.26 to 1, is known. In the same way Spica Virginis has a period of only 4 days, and masses at least 9.6 and 5.8. No such binary has yet been found with masses much less than the sun's; but there is a star of magnitude 6.4 with a period of 14 days and masses at least 76 and 63 times the sun's. It is known as Plaskett's star and is the most massive known with any certainty.

Eclipsing or Algol variables are binary stars

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in which the plane of motion passes nearly through the sun, and the stars eclipse one another at each revolution. For such stars it is possible from a careful study of the light-curves to discover almost everything about the system, and fantastic some of them are. For example, there is a star W Crucis of magnitude at maximum 8.7, and a period of $198\frac{1}{2}$ days (very long for such a variable), which loses 0.62 magnitude when the smaller star crosses in front of the larger and makes a very partial eclipse. The brighter star gives 9 times the light of the fainter, but has only twice its diameter, and the radii of the two together nearly equals their separation, so that the stars are almost in contact. Their densities are respectively one- and three-millionths of the sun's density, or in the mean one five-hundredth that of air; yet they eclipse one another. All this, and something more, but not their masses can be discovered by studying the variation of their combined light.

The mass comes when the real velocities are measured with the spectroscope, and it will be interesting to see if, like most of these stars, the masses are rather greater than the sun's. One star there is, V Puppis, which is 19 times as great, but that is exceptional. In general the three methods available concur in saying that the masses of stars are usually of the same order

GIANTS AND DWARFS

as of the sun, not often 10 times greater nor less than a fifth. This is a range much smaller than the range of density or of luminosity. To find the density is a matter of simple arithmetic when the diameter and the mass are known, and the results range from a millionth to a hundred thousand times the density of water, the former figure belonging to giant red stars like Antares or Betelgeuse: the latter to white dwarfs like the companion to Sirius or van Maanen's star. But it is necessary to say that a giant star cannot have so small a density throughout. At the centre it must be very dense, and therefore at the surface even much less dense than the above average figure.

The luminosities of the stars, which are determined at once when their apparent and absolute magnitudes are known, have also a great range, from 300,000 times the sun (S Doradus) to one fifty-thousandth (Wolf 359), and as the brightness per unit of surface depends upon the temperature of that surface, which varies from about $1,600^{\circ}$ for the deep red long period variables to perhaps $70,000^{\circ}$ for a few stars of type O, the radiation per square inch varies from about a third to 28,000 horsepower.

The Cepheid variables are so important in modern astronomy that we must summarize in more detail than usual what is known about the

THE STARS

brighter of them, nine in number, which have been most thoroughly studied. The brightest is the Pole Star, so long taken as a standard of magnitude, and now convicted of varying, though only by a tenth of a magnitude, in a period slightly less than four days. Three others are fairly bright stars in the northern sky: Delta Cephei, the father of the family, Eta Aquilæ, and Zeta Geminorum, and one, I Carinæ, of the same brightness in the south; the four others are fainter. All but one of the stars are of spectral type much like the sun, and of nearly the same surface temperature: yet they are from five to ten magnitudes, from a hundred to ten thousand times more luminous, and consequently very much bigger, so that although they are massive, from five to fifty times the sun, their densities are enormously less.

When they are observed with the spectro-scope they exhibit variable velocities in the same period as the light changes, just as Algol for example does; but when one calculates the size of the orbit in the ordinary way, it comes out much less than the size of the star, which is absurd. The velocities of approach and recession are therefore not orbital, but are due to the star pulsating, swelling up and shrinking over a sixth of its radius. Now for Delta Cephei this means that the surface of the star rises and

CEPHEID VARIABLES

falls through a range of about two million kilometers every 5.37 days, and it has been doing this in a period which has diminished, if at all, less than a tenth of a second per year since it was first determined in 1785. It is entirely mysterious, whence comes the energy to maintain these tremendous pulsations. Contraction under gravity apparently cannot account for more than a five-hundredth part of it.

We have gone into so much numerical detail to emphasize the extraordinary progress that has been made in the last twenty years or so. But we must be careful to avoid thinking that so much can be known about all the stars with our present means of observation. The great majority are neither near enough to let us measure their distances directly, nor bright enough to let us do it with the spectroscope. Few are large enough to let us measure their diameters directly, and not many are eclipsing variables. From stars of rather special classes we have derived laws which we should like to hope are general, such as that stars of high luminosity are stars of exceptional mass, and up to the present we have not found ourselves contradicted, but there is always the possibility that the material on which such statistical laws are based is not representative.

From time to time a new star will suddenly blaze up, telling of some sort of catastrophe in

THE STARS

the heavens. Every year or two they find, on the photographs which are accumulated at the Harvard College Observatory, evidence that a star has appeared suddenly, declined gradually, and generally disappeared again before it had been recognized. When the star is bright, it may be caught before its decline has proceeded very far, and even when still upon the upgrade. Nova Persei No. 1 was found by Dr. Anderson of Edinburgh. On 1901 February 21 the sky cleared after midnight, and Dr. Anderson began his regular work of comparing the sky with star charts, field by field, in the hope of discovering new variables. He once described to the author how, becoming tired at the telescope, at twenty minutes to three in the morning he leaned back to rest a moment, and saw in the constellation Perseus the bright new star. Unable to believe that so bright an object could have escaped previous notice, he made diplomatic inquiries early next morning at the Royal Observatory, Edinburgh, and learned that they had no news of any special interest. Then, said he, he knew that he was all right.

At the time of discovery the star was of magnitude 2.7; that is to say, about half as bright as the Pole Star. A photograph taken only twenty-eight hours before, by Stanley Williams at Brighton, showed stars nearly to the twelfth magnitude, but no trace of the Nova, whose

NOVAE

light must have increased, therefore, at least four thousand times during that interval. In another day and a half it had become the brightest star in the northern sky; then it began to diminish, at first rapidly, afterwards more slowly, with large fluctuations which embarrassed alternately those who sought to show the new star, and those who wished to point out that it had disappeared. By June it had become invisible to the naked eye, and thenceforward it faded slowly into a faint variable.

The present century has been rich in new stars, having begun well with Nova Persei No. 1. Several have been conspicuously visible, such as Nova Aquilæ in 1918, Nova Pictoris in 1925, and Nova Herculis which was found by Mr. Prentice, an ardent meteor observer at Newmarket, only a few days before this passage was written. These stars have the same general history, of appearing very suddenly and fading away rather rapidly; of exhibiting quite a different spectrum for the first few days from afterwards; and of fading away eventually into the faint generally variable stars which they doubtless were before the outburst. But they have individual peculiarities: Nova Pictoris appeared to divide into two; both it and Nova Herculis persisted in getting brighter after discovery for quite a long time. The spectra of all give plenty of evidence very difficult to interpret, but one

THE STARS

of them, Nova Pictoris, was studied in detail by the present Astronomer Royal when he was His Majesty's Astronomer at the Cape of Good Hope, and we have a fair idea of what happened. Before the outburst the star was apparently constant, rather brighter than magnitude 13. On 1925 February 18 it was fainter than 12, but on April 13 it was photographed at magnitude 3, though the rise was not remarked until May 25, when it was at 2.3. Thence it rose slowly to 1.2 on June 7; faded a little and rose again to nearly 2 at the end of July; faded again to 3.3 on August 4, and rose to 1.9 on August 7. From that date it faded away with small irregularities, less than usual, until in 1934 it was of magnitude 9, or some thirty times brighter than before the outburst.

For nearly two weeks before its first maximum it had the same spectrum and was therefore at the same temperature; and as it was brightening it must have been expanding, by about 14 radii of the sun per day, until it reached 400 times the diameter of the sun. Then it threw off gaseous envelopes which expanded outwards with great velocity. Meanwhile, the original star was contracting and getting much hotter, so that its spectrum changed to a type which indicated a temperature of $50,000^{\circ}$. Its absolute magnitude at maximum was -7.9 , or a hundred and twenty thousand times as luminous as

LONG PERIOD VARIABLES

the sun. Its distance was of the order of 700 parsecs.

One has been tempted to inquire whether we may regard new stars simply as exaggerated cases of variable stars. We have in such a star as Mira Ceti a case nearly as difficult to explain, which attracts rather less attention only because the outburst happens every 330 days, more or less. The brightness of this star is continually varying, and at maximum it is anything from a hundred to a thousand times as bright as at minimum. Another variable star of long period, Chi Cygni, has a total range of nearly ten magnitudes, or shines ten thousand times as bright on some days as on others. We can hardly believe that a catastrophe affects such stars every three or four hundred days; there must be some more normal explanation of the light-outbursts, though none as yet has been established.

It cannot be said that the outbursts of light in a new star are so immensely greater than those in some of the variables, that they must without doubt be ascribed to different causes. Yet it is not easy to assign them to the same cause, because the spectra of new stars are very different from the spectra of long period variables. The latter, when they are bright, show exceedingly brilliant lines of hydrogen in their spectra. The former, as we have seen, may reach

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their maximum brightness merely by expanding without changing their spectrum, more in the manner of the Cepheid variables, but much more violently. Moreover there are a few stars, P Cygni, Eta Argus, and S Doradus which seem from their spectra to be something like permanent novæ, expanding envelopes and all, and these are a great asset, because they suggest, nay compel us to believe, that the new star spectrum is not necessarily associated with a catastrophe. So far, indeed, have we now gone from that idea that it has been seriously argued that a nova-like outburst may be a normal incident in the life-history of any star.

One of the earliest and simplest classification of stars was by their colour. Some are bluish white, as Rigel and Sirius; some yellowish, as Capella and the sun; some reddish, like Aldebaran, Betelgeuse, and Antares; and merely by analogy with a heated poker it was natural to suppose that the whiter stars were the hotter. The conclusion was correct though the argument was doubtfully valid, since the surfaces of the stars are not solid but gaseous. The gases below the surface, however, are at pressure enough to shine as if they were incandescent solids, and if the spectroscope could observe them directly their light would be analysed into a continuous rainbow band of colour from red to violet. In fact the light has to pass

STELLAR SPECTRA

through outer layers of gas at lower temperatures, which absorb precisely those rays which they themselves are emitting though less intensely: so that the colour band of light, the spectrum, is crossed by dark lines which are arranged in patterns characteristic of the particular substance whose vapour is doing the absorption. Each element has a characteristic arrangement of lines, faint or strong, few or numerous, and the spectrum of the star is a mixture of the patterns belonging to all the elements whose vapours are mixed in the cooler outer layers of the star. More strictly, we have to say nowadays that each element has several characteristic patterns, depending upon the condition of its atoms, whether neutral, with the proper number of electrons, or ionized, with some of the electrons stripped off at high temperatures.

Prolonged comparison of the spectrum of our sun, which is the most convenient star to study in great detail, with the spectra of elements in the laboratory, has shown that of the 92 terrestrial elements (including two yet undiscovered but required to fill vacant places in the table of atomic numbers), 57 have been identified in the sun and 35 have not. These 35 include important metals, gold, platinum, mercury; the radioactive elements like radium and uranium; the inert gases argon and neon and others, but

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not helium; the important group of elements fluorine, chlorine, bromine, and iodine; and such characteristic things as phosphorus, arsenic, and selenium. One may say indeed that the more interesting terrestrial elements are not found in the sun, but that is far from saying they are not present there. Nearly half the lines in the solar spectrum are unidentified as yet, but probably not because they belong to elements unknown upon earth. It is much more likely that they belong to known elements in states that have not yet been imitated in the laboratory; and there is no reason to think that the sun contains any element that we do not know upon earth, or indeed that any such element exists except the two for which places remain in the table.

What is true for the sun is true also for the stars. We can prove that they contain many elements that are in the sun, and one or two that are known upon earth but not yet found in the sun. And though the spectra of stars differ so very much among themselves, it is not because they are composed of different elements, or even of the same elements in very different proportions, but rather that they differ so very much in temperature.

The present universally adopted classification of the star spectra has been worked out at Harvard, on a plan of giving letters to the principal

SPECTRAL CLASSES

classes of spectra and subdividing the class into sub-classes numbered from 0 to 9: a refinement which we need not consider in a small book. The original order of the letters has had to be changed, and many of them have dropped out. After many years of work there survive the classes O, B, A, F, G, K, M, and the present order is that of decreasing temperature.

The letter O signifies stars of a rare type, so hot that they shine nearly as incandescent gas, with bright lines, and their temperature is perhaps $50,000^{\circ}$ C. The B stars are characterized by hydrogen and helium lines and little else, helium fading out and other lines coming in as the temperature falls from $23,000^{\circ}$ to $12,000^{\circ}$ within the limits of the class. In class A helium is absent, and as one passes to F, G, K, the hydrogen also fades and the lines of iron and other metals become more prominent, especially those significant of low temperature, which is by this time down to $3,500^{\circ}$ C. Finally we come to class M with broad absorption bands due to compounds such as titanium oxide at $3,000^{\circ}$ or less. Even a brief and much too summary a sketch must go a little into detail, necessary because this spectral classification has become a terminology which one can hardly avoid now in talking about the stars. And to repeat: the change in the spectrum from class to class does not mean that some stars are made

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of helium and some of calcium and some of iron. These substances are all there all the time, but predominate in effect at different temperatures and in consequent different states of their atoms.

In 1911 there was little to say on the physical constitution of the stars, their masses, luminosities, diameters, and densities; but the preceding pages have given some account of how these important quantities have since been determined, and in them we have occasionally used the names giant and dwarf for stars of great and small luminosity, thus anticipating a little the result of the great generalization which was made in 1913 by Hertzsprung and by Russell. When the real luminosities of a few M stars were calculated from their measured parallaxes, it was found that they were either very high or very low, and the same was true in a less degree for the K and G stars. Hence arose their provisional division into two categories, of giants and dwarfs. Then Professor Russell of Princeton was inspired to make a diagram which has had an outstanding success. We cannot do justice to it by reproducing an actual example on this small page, but it is easy to describe in terms of the page.

Imagine that the left-hand margin is divided into a scale of absolute magnitudes from plus 14 at the bottom to minus 4 at the top, and that

THE RUSSELL DIAGRAM

the top margin is divided into compartments bearing the letters B, A, F, G, K, and M of the Harvard classification from left to right. Then any star whose absolute magnitude and spectral type are known may be plotted on the diagram. When a few hundreds are plotted they show at once a peculiar distribution, being crowded along a line between the points corresponding to Absolute Magnitude 0 Type M to A.M. 2 Type A, that is to say along a line sloping a little downwards across the upper part of the page from right to left; and then along a line running diagonally down from A.M. 0 Type B to A.M. plus 10 Type M, that is to say, along a line from the top left-hand corner of the page to the bottom right-hand corner. In the M and K columns there is a complete separation between the bright and faint, the giants and the dwarfs. In the G column it is less marked. In the A column there is a great scarcity of giants and no dwarfs, but a great concentration about A.M. plus 4. The A's are all clustered about A.M. plus 2. The B's are few, because as we have already seen it is impossible to determine their luminosities from their spectra, and very few have measurable parallaxes.

Every fresh plot with richer material has confirmed the essential rightness of this instructive diagram of 1913. The last, published from the Mount Wilson Observatory in April 1935, adds

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to a scattering of super-giants in the region of A.M. minus 3 and 4, but amply confirms the original pattern of the distribution. The giants of M, K, and G are numerous, but the greater part of the stars are gathered along the descending diagonal, which has received the name of the Main Sequence.

The arrangement of stars in the main sequence exhibits the law that the massive stars are on the whole the brightest and the hottest, and that as they cool and change from white to yellow and then to red they are all the time losing mass. It is a principal ground for believing that the radiation of the stars is supported by the transformation of mass into energy; expressed in tons the loss of mass is extraordinary: a star like the sun losing 4,000,000 tons a second, yet even at this prodigious rate lasting for 1,000 million million years without much apparent change. One may believe that not all the elements dissipate themselves into energy at the same rate, and that the very bright and massive stars are living faster at first by the destruction of elements heavier than any we know that have disappeared altogether into radiation before the star approaches middle age, by which time it is living more slowly, and tending to a prolonged old age of a slow but perfectly sufficient consumption of mass.

No one has yet explained the nature of the

MAINTENANCE OF RADIATION

process by which this transformation takes place, but the belief that it does so was strongly supported by mathematical and physical arguments that have been somewhat disturbed by recent discoveries in atomic physics.

Just how the giant red stars are related to this scheme is rather obscure. They have low surface temperatures, but radiate much heat, and must therefore have enormously large diameters, as has in fact been verified in a few cases by direct measurement.

It was perhaps the greatest feat of modern observation to realize the method, proposed long before by Michelson, of measuring the diameters of stars by a most difficult optical method with the 20-foot interferometer made for that purpose at Mount Wilson by Pease, and mounted upon the 100-inch telescope. The optics we cannot attempt to describe; the result was that it was found possible to measure a few of the brightest red giants, and to prove that their diameters are immense: so much so that if the sun were a red giant he might nearly fill the solar system.

There is another way of measuring a star's diameter. By piecing together information from various lines of research one can form a fairly close estimate of the effective temperatures of the stars from the character of their spectra. They run from about $2,500^{\circ}$ to $70,000^{\circ}$. One

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can also measure in some cases the total radiation received from the stars; and then knowing that total radiation and the temperature of the surface we can calculate how big the surface must be to give that amount of radiation, and so knowing the surface we know the diameter. Another path, one might say, with plenty of pitfalls. Again we are rather surprised to find that the diameters obtained thus for the few stars which have actually been measured with the interferometer agree quite well, and we are fortified in applying the method to other stars which cannot be measured so directly.

Apart altogether from the main sequence, in the lower left-hand corner of the diagram lie a small group of remarkable stars, the white dwarfs. They are very small, more like the earth than the sun in size. They have maintained their white colour while losing most of their luminosity, but in the process have reached enormous densities altogether beyond anything formerly conceived. The companion of Sirius has a density fifty thousand times that of water. Its atoms can be packed so close only by losing all their electrons and being reduced to mere bare protons. Jeans has called them degenerate, radiating so little energy that annihilation and decay are almost entirely checked. "We may think of the white dwarf state as a final state from which change and decay have so nearly

WHITE DWARFS

disappeared that a star which shrinks to this state acquires a new lease of life for a period of thousands of millions of millions of years—we can only wonder to what purpose.”

CHAPTER VIII

STAR CLUSTERS AND NEBULAE

AT several points in the sky the unaided eye can see something hazy and ill-defined, which is certainly not a star, and scarcely looks like a group of small stars close together. One is in the sword of Orion, another in the constellation Andromeda, a third in Hercules; and there are others in the southern sky. One at least, that in Andromeda, had been known to the Arabian astronomers, if not to the Greeks. Galileo's telescope discovered that in Orion, and Halley more than two hundred years ago found the third. All three are easily seen without telescopic aid when one knows where to look. As telescopes were gradually improved these patches of light were carefully studied to see what could be made of them, and the heavens were scanned to discover more objects of the same kind. A French astronomer, Messier, was foremost in the search, so that in the year 1776 he was able to publish a catalogue of 103 of these objects, and they are still for convenience and brevity often referred to by their

HERSCHEL'S CATALOGUE

numbers in this celebrated little catalogue. Some of these Messier himself could see were nothing but clusters of faint stars close together; others could not be resolved into stars, and these were the *nebulae* proper (Latin *nebula*, a cloud).

The most famous and the most enduring work of the Herschels is their catalogue of *nebulae*, recorded in the course of their survey of the sky from pole to pole. When William Herschel began his methodical examination of the sky, field by field, scarcely more than a hundred *nebulae* were known. When his son, Sir John, long after his return from the Cape and the southern skies, was able to bring together into one general catalogue (dated 1864) every nebula and star-cluster that was known, their number exceeded five thousand; and all but a small fraction had been found by his father and himself.

The *nebulae* and the star-clusters were catalogued together, for the time had not come to draw any clear line of distinction between them. In early days it had often happened that what had appeared to one observer as a filmy patch of light had been resolved into clearly separate stars by the more powerful instrument of another. What more reasonable than to suspect that every nebula could be so resolved, had we telescopes sufficiently powerful? So far as was

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then known, stars, and stars only, shine by their own light. Until proof to the contrary was obtained the simplest, and therefore the preferable, explanation of the nebulæ was to suppose that they were clouds of stars, but so immensely distant that the stars could not be separated one from another.

Thus each builder of a greater telescope strove after the resolvability of nebulæ. But the nebulæ in general refused to be resolved. Some of their secrets they gave up, one by one. It became more and more evident that they were by no means all of the same kind. In some the light was curdled, like the filmiest cirrus cloud high up on a fine summer day; others were made of wisps and streaks like a gauze veil torn to shreds; others again were clear cut and sharp in outline, like pale ghosts of planets. Sharply separated from these were other nebulæ of a most remarkable form first revealed by Lord Rosse's great telescope at Parsonstown in Ireland—nebulæ in which spiral arms were wound about a central condensation. So exceedingly difficult to see, so much more difficult to understand and explain was this complicated structure, that astronomers with feebler instruments were not unnaturally at first a little disinclined to accept as reality the fantastic spirals that Lord Rosse and his assistants drew at the eyepiece of the great telescope.

SPECTRA OF NEBULÆ

That nebulæ should be resolved was indeed to be expected, but that they should be resolved not into stars, but into spiral arms still nebulae, was extraordinary, almost beyond belief.

The next great step in our knowledge of the nebulæ was to come by analysing this light. The crucial experiment was made by Sir William Huggins. In the year 1864 he turned his spectroscope to a nebula in the constellation Draco and read its secret at a glance. The light was not starlight, but something very different; light which came from glowing gas, shining in space by itself. In a short while came the explanation of the fact that the nebula in Orion could never be resolved into stars. It was not made of stars but was an immense cloud of self-luminous gases—of hydrogen; of helium, then unknown upon earth, though now it is used for filling airships; and of a gas which produces two bright green lines in the spectrum of the nebulæ, never yet reproduced in the laboratory, but on purely theoretical grounds attributed with confidence to oxygen minus two of its electrons.

We may have pictured to ourselves the delight with which Sir William Huggins examined his first nebula and found that it was gaseous, and may now imagine with what surprise he found, on turning to the great nebula in Andromeda, that it was not gaseous. Gaseous nebulæ, in-

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deed, have proved to be the exception rather than the rule. Though most nebulæ are so faint that their light is insufficient for analysis, we may argue from appearance; and since the nebulæ which are certainly gaseous differ very much in appearance from those which are certainly not, while a very great majority of the nebulæ belong in appearance to the latter class, then we may say with some confidence that the majority, the so-called white nebulæ, are not gaseous.

The power to classify the nebulæ by their apparent structure has come with photography. The eye and the pencil are incompetent to portray such very faint and delicate objects. How well the sensitive photographic plate succeeds where eye and pencil fail may be seen in any one of the many collections of astronomical photographs which are now available.

We have spoken of the famous achievement of Lord Rosse's telescope—the discovery of the spiral nebulæ, and of the natural half incredulity with which this surprising discovery was received. It was embarrassing, this complication of structure, so unlike anything else in heaven or in earth. But there was the consolation that the strange spiral form was rare and exceptional. It was curious and interesting and most impossible to explain, yet at any rate there was no reason to suppose, fifty years ago,

SPIRAL NEBULAE

that the spiral nebula was a common feature of the universe. Only a few were known, and if they could not be understood, they could at least be set apart as rare creatures, outside the ordinary run of things.

By the application of photography this comfortable belief was shattered. In the early eighties Common showed that with the invention of the dry plate nebular photography had become possible. By the middle eighties Isaac Roberts had begun his steady systematic photography of all the brighter nebulae; ten years later Keeler with the Crossley reflector at the Lick Observatory made a great advance towards perfection of results; and in the last twenty years Mount Wilson has shown what great results can be obtained by courage and consummate skill in instrument construction.

At the very outset these photographs confirmed to the full the accuracy of Lord Rosse's early observation, that many of the brightest and finest nebulae are formed of spiral arms, generally two. They spring from a central condensation at two diametrically opposite points, wind with more or less perfect regularity around the centre, and are studded along their length with bright knots that look as if the nebulous stuff were there condensing into stars. Year by year the number of these spirals has grown. They rapidly outnumbered the gaseous

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nebulæ; and it began to look as if nearly all the white nebulæ would prove to be spirals, so soon as they were successfully photographed. But in fact there are many which show no trace of spiral structure. They do, however, so strongly resemble the structureless central regions of many spirals that we need not hesitate to count them in the same family, known nowadays as the non-galactic nebulæ, because they are not found in the Milky Way.

The gaseous nebulæ, on the other hand, are of many families: the stellar, hardly distinguishable from stars except by their spectra; the planetary, pale small discs of greenish light, variously mottled or resolved into rings, and generally with a central star; the wispy, like the pair in Cygnus, which are perhaps relics of a large planetary; the bright structures full of detail surrounding Theta Orionis or Eta Argus; or the vast vague nebulosities involved in some of the Milky Way star-clouds, often associated with dark structures which may be absorbing matter in front of them: but on the other hand, maybe, belong to the nebula itself, a possibility which has been somewhat neglected in discussion.

These last objects are much the largest things in the sky, extending each over quite a number of square degrees. To call them nebulæ hardly does justice to their size, as indeed Sir

EXTENDED NEBULÆ

William Herschel must have felt when he brought them together in a special list, not of nebulae, but of "regions affected with nebulosity." Of late years this happy phrase has been revived, and for the first time they have been worthily portrayed. Before the advent of photography this was quite impossible, for the simple reason that they are too big to be seen in a visual telescope, very much in the same way that the zodiacal light and the Gegenschein are also too big. For the field of view of a telescope is practically limited to a single degree, and in general the larger the telescope the smaller the field of view. Hence it is no paradox to say that an object is too big to be seen in a telescope.

When a nebula more than fills the field of view, one is conscious only that the background is dimmed and that the faint stars appear dulled for want of contrast. But by sweeping the instrument backwards and forwards one is able to trace out the nebulous region to this extent, that one can say: Here the background is clear and black; there it is full of vague light and the stars are dulled. The camera, with its big field ten or fifteen degrees square, has superseded this unsatisfactory groping, and is now able to let us stand back, so to speak, and take in at a glance these wonderful regions. Look at one of Barnard's

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pictures of the Milky Way in the constellation Scorpio, near the star lettered Rho. We are struck at once by a curious dark lane, almost empty of stars, which runs across the plate for several degrees, and appears to be blacker than the background of sky. For a moment we wonder how this is possible, and then we notice that over the greater part of the plate the background is not really black at all. We are in one of the regions affected with nebulosity.

It was for long impossible to suggest how an excessively thin distribution of gas at what must be near to the temperature of space could glow so bright that it was not only visible through our telescopes but the light could be analysed, and one was tempted to speculate whether the effect might be due to something like the glow produced by electrical discharges in nearly exhausted tubes. It is now believed that the light is not inherent but either reflected or stimulated by the intense radiation from very luminous stars in the neighbourhood. We had not known until lately how bright some stars might be. But the light from these stars is largely continuous. It cannot therefore be merely reflected light that shines in the nebulae that are seen to be gaseous through the spectro-scope; there must be some transformation of energy, recently explained in terms of the "quantum theory."

ABSORPTION OF LIGHT IN SPACE

Some nebulae indeed there are which have the spectrum of the stars of the neighbourhood. Such is the curious streaky nebula of the Pleiades; and reflected also was the light that made the moving nebula around Nova Persei.

Apart from the nebulae of definite form there is a great extension of vapour, and doubtless also of dust in the interstellar spaces. Much of the vapour is calcium, which produces its characteristic absorption in the spectra of stars beyond; which has been distinguished because these particular lines do not share in the displacement caused by the motion of the stars. There must also be much dust driven away by the pressure of light from the vapours surrounding highly luminous stars, and it has always been a question how much light would be lost by obstruction and absorption in its passage through space. Opinion has gone up and down, some results being large and some almost negligible. The best criterion for scattering by dust is that it produces a reddening in the objects seen through the haze, as is familiar enough to us at sunset; and the most recent determination of absorption in space, based on studies of the colour-index of very different objects, gave a result which was appreciable, but made no alarming difference in the estimates of great distances from the comparison

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between the absolute and apparent magnitudes of stars: of which more later.

Historically the nebulæ and star-clusters are closely allied, in the first catalogues of Messier and Herschel, and because in early days they were sometimes mistaken one for the other, which led to the early belief that all nebulæ are resolvable into stars in a good enough telescope. The discovery that some nebulæ are gaseous put an end to that idea, and nineteenth-century opinion went to the other extreme, that no nebulæ are resolvable. But that in turn is controverted by recent photographs of the larger spirals with the 100-inch of Mount Wilson, in which variable stars have been detected.

Of star-clusters we have now to distinguish three kinds: first the recently discovered moving clusters of bright stars with common parallel motion in space, which are not clusters at all in the usual sense of stars apparently close together. On the contrary, the Ursa Major moving cluster includes Sirius among its members, and our sun is within the cluster, so that we see its members all round us. Secondly come the obvious groups of stars like the Pleiades and Praesepe, and the fainter but similar loose aggregates of stars in the Milky Way: open or coarse clusters that in general belong to the Galaxy, and are often associated with diffuse nebula. Thirdly, and by far the most important,

GLOBULAR CLUSTERS

are the globular clusters, strongly condensed to the centre, where the stars are so crowded that they are barely distinguishable, and among them many variable stars of the Cepheid kind, with very short periods of a day or so. Perfect timekeepers these cluster variables are, blazing up to four times their minimum brightness and more slowly fading away to it, in periods closely related to their absolute brilliance: perhaps the most incredible of all the unlikely things in the Universe that are nevertheless true.

Until lately it was possible to say that the globular clusters as a class had this peculiarity, that new members were hardly ever discovered. By far the greater part of them are in the catalogues of the Herschels. One or two of such have proved to be really spiral nebulae; a few more have been discarded as close clusters but hardly with that particular degree of condensation which marks the globular. Just a few had been discovered since the time of the Herschels, but the total had remained about 100, while minor planets and spiral nebulae had multiplied a thousandfold. This was a certain reason for thinking that they have a peculiar distribution, and were not like most things, found to extend farther, the more powerful the means of search; and this was perhaps what was in Shapley's mind when he identified

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them on what seem rather inadequate grounds with our own galaxy (Chapter IX).

A recent discovery has falsified the statement that no new globular clusters are ever discovered, and seems to have proved Shapley's guess sagacious. The astronomers at Mount Wilson have recently announced the discovery of about 130 globular clusters in the Andromeda Nebula. They are of course excessively minute in apparent diameter, and no one would be justified in asserting that they are globular clusters from their appearance in published photographs; but one must accept the judgment of those who examined the original negatives. These clusters are distributed over a space several times as big as the greatest extent of the nebula which has ever been photographed, and they cover a more or less circular area, but they are not to be found outside a pretty definite boundary, and seem clearly to belong to the nebula system. Their distribution is in fact not unlike that of our own globular clusters. The interesting question then arises, Why is it that if our own system and the Andromeda Nebula are essentially flat as they seem to be, judged respectively by their internal and external aspects, the globular clusters which belong to them do not share in this flattening? To that question there is at present no answer.

DISTANCES OF NEBULÆ

When the chapter on Nebulæ was written in the spring of 1911 for the first edition of this book, we said nothing at all of the distances of the nebulæ and clusters, for there was nothing to say. Our whole knowledge of this matter has been gained in the last twenty years. In 1914 a distance of 10,000 parsecs was the greatest distance that an astronomer had occasion to mention; the greatest that had been measured in 1934 was about 40,000,000 of that unit.

The enormous extension which has been given to our knowledge of the universe during these twenty years, and the unexpectedly large distances which are now roughly measurable, depend upon methods which are physical and not geometrical. They go back in a sense to the older method of judging the distance of a star from its brightness, but with this important difference: we are now able by various methods to determine what is the real intrinsic brightness of a star, whence by comparison with its apparent brightness it is of course easy to estimate its distance.

The key to the method of employing these stars as distance-measures was found in the lesser Cloud of Magellan. In that star-cloud there are a great number of these stars, which were studied in great detail at Harvard on plates taken at their southern station in Peru.

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After many months of tedious identification and measurement upon dozens of plates, Miss Leavitt made the capital discovery that the brightness of these stars was rather strictly related to the period of variation; and they were all in the smaller Cloud of Magellan, (Chapter IX), certainly at a great distance, but reasonably assumed to be more or less compact; so that at any rate to a first approximation these stars could be taken as at the same distance from the earth. Thus was established the first draft of the famous Period-Luminosity Law, which is so powerful in modern astronomy.

The work at Harvard found a relation between the period of the Cepheid variables and their apparent magnitudes, and it remained to find the zero-point by which the apparent magnitudes could be translated into absolute magnitudes and the distances determined. There were only two or three Cepheid variables within range of direct geometrical measurement, and for a few more one could obtain some idea of their distances from the discussion of their proper motions. Little by little it was found possible to fit in this rather poor material to the relatively very well determined curve derived from the Cloud of Magellan, and in this way a zero-point was established, at first by no means securely.

The next step was to fit on the cluster-vari-

CLUSTER VARIABLES

ables at the other end of the curve, which was relatively easy. When a smooth curve was thus established and it became possible to determine from their periods the absolute magnitudes of variable stars whose mean photographic magnitude was really faint, about the 16th magnitude, it was at once seen how powerful a tool had been forged. The brighter and better studied globular clusters proved to be at distances greater than had been anticipated, from some 4,000 to 40,000 parsecs away; and when their distances were compared with their apparent angular diameters it was seen at once that they were roughly of the same size, which gave a method of determining, though less accurately, the distances of the further clusters which had not yet yielded up any variable stars to the scrutiny of the photographic telescope.

The next step was a long one. We had been accustomed to think that the spiral nebulae are irresolvable: studded it is true along their spiral arms with condensations, but without any stellar detail that clearly belonged to the nebula itself, and was not merely superposed. One of the greatest and most remarkable triumphs of the great reflecting telescopes at Mount Wilson was to discover a great number of Cepheid variables in a few larger spiral nebulae, which evidently belonged to the nebulae

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and were not merely by chance in the same direction, because their distribution was similar to though more extended than the nebulæ as photographed, and there were none in adjacent parts of the sky. These variables are so faint that they can be tackled only by two or three existing telescopes. But on the assumption that the Period-Luminosity Law is well-determined to its limits, the distances of even the brighter and presumably nearer spiral nebulæ ran up to a quarter of a million parsecs.

Naturally enough this immense extension of our measuring scales did not escape criticism. It was easy to point out that a very large structure had been based upon what looked like a very insecure foundation. There was considerable doubt about the zero-point, and astronomers of conservative minds inclined to the belief, or perhaps the hope, that a building so insecurely founded would soon collapse. But that idea must now be given up. Prolonged investigations of the zero-point have shown that it was fixed at first too low, and revisions of the scale have always tended to reduce the scale a little: that is to say that the first distances were somewhat overestimated. But it does not seem possible to reduce them by more than about 30 or 40 per cent. provided always that one is entitled to assume that the same laws hold all over the universe.

PERIOD-LUMINOSITY LAW

This is a fundamental question which it is difficult to discuss, because it is in our present knowledge very much a matter of opinion. How can one be sure that a star which in one part of the sky, namely the Lesser Cloud of Magellan, performs the surprising feat of blazing up to four or five times its minimum brightness at perfectly regular intervals of from 20 to 60 hours, and follows the simple but inexplicable law that its average brightness is strictly related to the period, would continue to do the same if it were removed to quite another part of the sky: or, more strictly, that stars which have developed the same general characteristics in different parts of space have developed them according to the same law upon the same scale? We know that a simple pendulum clock removed from Paris to Cayenne was found to lose two minutes a day and gave the first indication that the earth is not a sphere but a spheroid. In ignorance of the causes which relate the period to the luminosity, why should we suppose that the effects are always the same?

The only answer to these questions seems to be that if your arguments are wrong, you will sooner or later find yourself involved in contradiction. It is indeed the chief business of the scientific man to apply as many tests as possible to his theories and to his empirical laws,

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and it is only by the absence of contradiction that he can be assured that these laws are well founded. The conservative astronomer has been looking for, expecting, almost hoping that contradictions would appear; but it must be confessed that up to the present no serious contradiction has been found. From time to time there were apparent discrepancies: but on the whole they have been successfully removed. If one argues that one is not entitled to believe *a priori* in uniformity of the universe, the answer is that so far as our knowledge goes it does appear to be very much more uniform than might have been expected.

The case may perhaps be illustrated by considering what would happen to a traveller who estimated his distance from the people he saw, by measuring the angles which they subtended when they were standing erect, and assuming that all the men were, say, 5 feet 10 inches high. He would not be justified *a priori* in this assumption, and he would be rather seriously wrong among the inhabitants of Ruanda, who sometimes run to 7 feet, or among the pygmies of the Congo forest. But experience would show him in the end that although he might have to revise his scale a little, there was in fact a law of nature which said that men of a tribe were so rarely in the average over 6 feet 6 inches or under 4 feet, that he would not be

LIMITS OF SIZE

widely wrong if he worked on his first assumption. The same kind of argument may be applied to the universe; the more we know of it the more evident does it become that there are standards of luminosity and of mass that a star is not likely to exceed. How far it may fall below them matters the less since in these distant regions with which we are dealing, it is only the very brightest objects which are seen at all, and to that brightness there does seem to be a fairly well defined upper limit proper to each class.

One might have thought that this was reasonable enough in regard to brightness and mass of individual stars, but that there seems no reason at all why the size of the groups into which the stars were aggregated should not vary over a wide range. Yet the evidence is on the whole against it. We have seen already how the distances of the farther globular clusters were estimated at first merely by their size as compared with the nearer. The method was undoubtedly crude, but up to the present it has not led to any serious contradiction, and there is therefore less reason to object to a provisional estimate of greater distances such as those of the fainter spiral nebulæ, by methods based upon the assumption that they are all more or less of the same size and brightness, and that they only appear smaller and fainter

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because they are farther off. It seems therefore that what is markedly untrue for individual stars is more or less true of the greater systems in which those stars are gathered.

All our present knowledge goes to show that the stars we can see in the very distant clusters of nebulae are stars of exceptional brightness, and that there is a rough limit to the brightness of objects of different kinds.

Cluster variables, for example, do not have absolute magnitudes that run past the zero into the negative side. New stars, or rather temporary stars, run much brighter, to about -5 , but there is no evidence that they go brighter. If, then, we find that there are in the Andromeda Nebula temporary stars appearing and fading out again, as has been observed, we may provisionally consider that their absolute magnitudes are not brighter than -5 , and from these obtain also a modulus. The method rests upon a bold assumption, but gives a distance to the Andromeda Nebula in fair agreement with that found from the Cepheid variables. If this is confirmed in a few other cases, then we may be bold to use the method generally: at least until we come up against a contradiction. In the same way the bright blue-white stars and other classes have rough upper limits of brightness, and so this method of the modulus gives us a powerful method of estimating the

DISTANCE OF SPIRALS

distances of objects otherwise hopelessly beyond our reach.

Further, the nearer spirals were found to have much the same total luminosity. If the rule holds, the distances of the smaller spirals may be estimated from their brightness alone. Finally, the displacements of lines in their spectra interpreted as showing very high radial velocities were found proportional to the distances. By a courageous inversion of the process, the distances of still further nebulae were estimated from the displacements. And that, for the time being, is the last word in the measurement of extreme distances.

We thus arrive at the following classification of nebulae and clusters: the smaller gaseous nebulae, and the looser, more open clusters of stars, especially the moving clusters, are relatively near neighbours of ours, and so perhaps are some of the dark obscuring nebulae that just blot out patches of stars in the sky, without any apparent relation to the larger faint gaseous nebulae that are mixed up with the star-clouds of the Milky Way. At much greater distances are the globular clusters of our own system, many of them probably farther away than any of the principal star-clouds. At distances very much greater still are the spiral nebulae, that have now taken upon themselves the status of distinct systems, of island universes as they

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have been called, comparable with the whole of our own system of stars and clusters. This aspect of them we must relegate to the next chapter. Meanwhile, it will be convenient to describe a little more in detail the appearance and structure of the various classes of nebulae and clusters. Without plates it is difficult to give any idea of nebular appearance: one can but give certain crude description, enough to suggest a primitive classification.

The constellation of Orion is deeply involved in nebulosity. Around the middle star Theta of Orion's sword is a complex mass of light, curdled, with sharply defined dark markings, a large bite taken out of it in the north-east quadrant, extensive areas of streaky light all about it. Running south from the eastern (left-hand) star Zeta of the belt is a long irregular edge of light dividing sharply a region full of stars and diffused light from a neighbouring region with few bright stars and almost no faint, though the background is dark. Biting into the bright region is a sharp dark silhouette like a horse's head, outlined with light. In the neighbourhood are regions of patchy nebula with dark streaks, like the middle of the Theta nebula; and all around the constellation is a broad lane of faint light.

The first early application of the spectro-scope showed that the Theta nebula has an

ORION NEBULA

emission spectrum, of relatively few bright lines of hydrogen, helium, and oxygen. Later a few determinations of radial velocity were interpreted as evidence of rotation as a whole, and premature calculations of the nebula's mass were made. But latterly more numerous observations at many points have shown that the effect is not regular, and is to be explained by turbulence rather than by rotation. From the supposed rotation in a period of several hundred thousand years it was calculated that the mass of the nebula is of the order of 10,000 suns, but that even so the density of it is only a thousand-billionth of air at sea-level. These figures have no kind of reliability, but serve to show that even a bright nebula may nevertheless be inconceivably tenuous.

Diffuse nebula is, in the opinion of Hubble, essentially dark. If there is a bright hot star of type O or B₀ in the neighbourhood, the sparse molecules of gas are stimulated by resonance or fluorescence or some such effect, and give an emission spectrum of hydrogen and helium and ionized oxygen. If the involved star is of type B₁ or cooler, the gas molecules do not shine, but the solid particles of dust reflect the light of the star, and the spectrum is a faint duplicate of the star's spectrum, just as the spectrum of reflected sunlight is a faint duplicate of the sun's. Hubble has actually reduced

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the thing to a rule, that nebula stuff at a distance of 10 parsecs from a star of absolute magnitude minus 5 will be bright enough to be photographed in three hours with a reflecting telescope of the usual 5 to 1 ratio, and by the usual inverse square law one may calculate the rule for any other distance, as 1 parsec for a star of absolute magnitude zero. This rule seems plausible enough for a nebula like that of Theta Orionis, which has a quadruple bright hot star at the centre, and gets fainter in all directions away from the centre. It does very well for most of the planetary nebulæ, which have central stars of type O, especially hot. But it does not seem to fit so well a long edge of nebula dividing light from darkness, such as that described south of Zeta Orionis; nor the big rather uniform North America nebula that is confidently said to be illuminated by the super-giant Alpha Cygni rather a long way away; nor the long wisps of nearly uniform brightness in the constellation Cygnus; nor does it explain why the Theta nebula is gaseous at the centre, but in the outer regions shines by reflected light.

A principal difficulty of these diffuse extended nebulæ is the relation of the dark to the light. Are the dark much nearer than the stars and luminous nebulæ, so that they just eclipse them accidentally, and have no relation with them

DIFFUSE NEBULÆ

either in structure or in space? If so, why does it so often happen that there seems to be a relation, a bright nebula at the head of a long lane of darkness, or a brightening of the luminous, more than can be explained by contrast, along the edge of the dark? There is here a field for inquiry, not yet very well cultivated.

We have as yet little precise knowledge of the distances of the diffuse nebulae, but they seem, judging by the proper motions of the stars involved, to be relatively near. The Pleiades must be about 100 parsecs away; the Orion nebula is by some placed confidently at 180 parsecs, but by others as far as 500; the America nebula is variously estimated at from 180 to less than 100. But what makes these estimates appear doubtful is that by similar reasoning the Rho Ophiuchi nebula, which seems so clearly to belong to the Milky Way, is set down at no more than 140: which badly requires confirmation.

The planetary nebulae number about 150. Their radial velocities are large, their proper motions small, from which we might infer that their distances are great. But there is always the possibility that they are relics of novæ, and that the shells of gas that a nova throws off just after it has reached its maximum are still visible, lighted up by the central star, and still expanding, which may account for the high

STAR CLUSTERS AND NEBULÆ

radial velocities, if these indeed belong to the shells and not to the nuclei. There is one nebula, the Crab in Taurus, which is measurably growing in diameter, and has been taken to support this idea that the small gaseous nebula are relics of novæ; but it does not do so very well, because it is far from looking like a typical planetary.

As the type of a globular cluster we will take that in Hercules (Messier 13). It is easily visible to the eye as a hazy star of about the fourth magnitude, yet it was not remarked as a cluster until Halley came upon it accidentally in 1714, more than a hundred years after the invention of the telescope: a fair example of the poor talent for discovery which afflicted the astronomers of the seventeenth century, and indeed until the epoch of Messier and Herschel. They were concerned with the solar system, and the places of the brighter stars, and did not realize how much there was to be found even with their imperfect telescopes.

The stars of a globular cluster are so condensed at its centre that they are barely separated with the largest modern visual telescope, and not at all with the best photographic. This richness falls off at first slowly and then rapidly away from the centre; and although the cluster has no very evident apparent limits, one may say roughly that its visual diameter is about

GLOBALAR CLUSTERS

ten minutes of arc, a third of the moon's. The Hercules cluster has in it only seven cluster variables, to be compared with the 150 or so in Omega Centauri and Messier 3. But such variables as there are provide a modulus of 15.1, a distance of 10,300 parsecs, and a consequent diameter of about 30 parsecs. But it should be remarked that in a few of the globular clusters with many variables they extend to several times the distance from the centre at which the cluster seems to stop, so that the true diameters are presumably several times as big as what Shapley calls the "working diameters."

All the evidence tends to show that the globular clusters are roughly of the same size, about 35 parsecs in diameters; that the stars we see in them are mostly giant red stars, and that presumably there are many times that number of fainter stars which we do not see. Evidently, therefore, the stars in them are clustered very much more thickly than those about our sun, in whose neighbourhood the average distance of star to star is several parsecs; and we can hardly conjecture what would be the richness and brilliance of our sky if our sun were one of the stars of a globular cluster.

As a typical spiral we may take the Great Nebula in Andromeda, which is roughly speaking an ellipse of about three degrees long and

STAR CLUSTERS AND NEBULÆ

one across. The central region is roughly circular, very bright compared with the outer regions and irresolvable, of a smooth even light, except for some markings which suggest dark lanes of obstructing matter. The outer portions of the nebula are formed of two long spiral arms, starting at opposite ends of a diameter, and traceable with interruptions over two or three circuits of the centre. Between these bright arms are dark obstructing stretches, often with fairly sharp edges encroaching in places on the luminous arms. As one goes farther out along the arms they are more broken up into groups and patches, and perhaps actually resolved in the outer regions. If not resolved, at least individual stars shine out upon them, Cepheid variables whose periods give their absolute magnitudes and a modulus, and novæ in surprising numbers, say 30 a year, whose absolute magnitudes with the above modulus agree very well with the absolute magnitudes of novæ in our own system, and so confirm the result from the variables. From these figures one may deduce that the distance of the Andromeda Nebula is a quarter of a million parsecs and its length about 15,000 parsecs. It has two companion nebulae, one on each side, looking like the inner region without the spiral arms of the great nebula.

From the Andromeda Nebula we may pro-

NOTE ON BOOKS

THERE are two general textbooks of high merit: the first modestly calling itself a revision of Young's famous *General Astronomy*, but in fact a work in two volumes largely new, and containing important original material: *Astronomy*, Volume I, *The Solar System*, Volume II, *Astrophysics and Stellar Astronomy*, by Russell, Dugan, and Stewart. Ginn and Company, Boston, U.S.A. Not dated, but 1927 or 1928. The second is *General Astronomy*, by H. Spencer Jones, Astronomer Royal. Second Edition. London, Edward Arnold and Co. 1934.

Of more special interest for its discussion of modern physical theories in their bearing on Astrophysics is *The Universe Around Us*, by Sir James Jeans, of which the Third Edition was published by the Cambridge University Press in 1933. The same author's *Astronomy and Cosmogony*, C.U.P. 1928, is of the highest importance, but full of difficult mathematics. Sir Arthur Eddington's *The Expanding Universe*, C.U.P. 1933, gives in brief form a clear account of the Relativity Theory of Lemaître, but does not hesitate "to plunge into matters of extreme difficulty when it seemed necessary for an adequate discussion of the problem." Dr. Harlow Shapley's monograph *Star Clusters*, published by the McGraw-Hill Book Company Inc. of New York, in 1930, contains much more than its title suggests and is invaluable for the student.

To keep abreast of recent work the student must refer to the periodicals. *The Observatory*, published monthly, ted unofficially from the Royal Observatory, Green-

NOTE ON BOOKS

wich, gives reports of the meetings of societies, reviews and notices of recent work, and general astronomical news. The *Journal of the British Astronomical Association*, the *Publications of the Astronomical Society of the Pacific*, and the *Journal of the Royal Astronomical Society of Canada*, are all full of interesting matter, largely unmathematical. The *Monthly Notices of the Royal Astronomical Society*, and *The Astrophysical Journal* are more severely technical; the latter contains all the principal results of the Mount Wilson Observatory.

Norton's Star Atlas, Fifth Edition, London, Gale and Inglis, 1933, shows the newly adopted official boundaries of the constellations.

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