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James Jeans

CHAPTER I

THE ASTRONOMICAL SURVEY OF THE UNIVERSE

1. THE moon, our nearest neighbour in the sky, is 240,000 miles away from us; a distance which light, travelling at 186,000 miles a second, traverses in a little over one second. The farthest astronomical objects whose distances are known are so remote that their light takes over one hundred million years to reach us. The ratio of these two periods of time—a hundred million years to a second—is the ratio of the greatest to the least distance with which the astronomer has to deal, and within this range of distances lie all the objects of his study.

As he wanders through this vast range with the aid of his telescope, he finds that the great majority of the objects he encounters fall into well-defined classes; they may almost be said to be "manufactured articles" in the sense in which Clerk Maxwell applied the phrase to atoms. Just as atoms of hydrogen or of oxygen are believed to be of similar structure and properties wherever they occur in nature, so the various astronomical objects—common stars, binary stars, variable stars, star-clusters, spiral nebulae, etc.—are believed to be, to a large extent at least, similar structures no matter where they occur.

The similarity, it is true, is not so definite or precise as that between the atoms of chemistry, and perhaps a better comparison is provided by the different species of vegetation which inhabit a country. Plants and trees, while differing in size, vigour, age and secondary characteristics, nevertheless fall into clearly-defined species. Basing our metaphor on this, we may say that recent extensions in telescopic power have revealed no new species of astronomical objects, but have merely multiplied the numbers of examples of objects which belong to known species. For this reason we may suppose that we are already acquainted with the principal species of astronomical objects in the universe.

The task of the observational astronomer is to survey and explore the universe, and to describe and classify the various types of objects of which it is constituted, discovering what law and order he may in their observed arrangement and behaviour. But only the dullest of human minds can rest content with a mere catalogue of observed facts; the alert mind asks always for the why and the wherefore. How comes it that these various classes of objects exist, but no others? What is the relation between them? Does one of them for instance, produce, or transform into, others? If so, what is the sequence of these changes? How did this universe of objects begin, and what will be its final end? If the heavenly bodies can no longer be regarded as having been created merely to minister to man's pleasure and comfort by illuminating the earth, what purpose, if any, do they serve? And if life, and human life in particular, can no longer be supposed to be the central fact which explains everything, what is its relation to the magnificent, stupendous, almost terrifying, universe revealed by astronomy?

To these obstinate questions observational astronomy provides no answer. Her task is limited to a mere description of the universe, which others may interpret if they can. Another science, cosmogony, provides material that may help to this end, which those who essay to interpret the universe can only disregard at their peril. Cosmogony studies the changes which the play of natural forces must inevitably produce in the objects discovered by the astronomer; it tries to peer back into their past and to foresee their future, guided always by the principle that the laws of nature have moulded the present out of the past, and will in the same way mould the future out of the present. Taking as its starting-point the still picture presented by astronomy, it attempts to create a living cinematograph film which will exhibit the universe growing, developing and decaying before our eyes. The sequence of events depicted in this film will be false unless the relation of each picture to the succeeding one is that of cause to inevitable effect.

Between observational astronomy and cosmogony there intervenes a third science, or branch of science, namely, cosmical physics. Cosmogony proceeds on the supposition that the matter of which the universe is constituted behaves as directed by natural laws, so that a knowledge as to the particular kind of matter with which we are dealing is a prerequisite to knowing what particular laws this matter will obey. As the laws of a liquid are different from those of a gas, a liquid star will behave differently from a gaseous star, and before we can predict the behaviour of a star we must know the state of the matter composing it. Cosmical physics attempts to provide the necessary information by deducing, with such precision as is possible, the physical nature and structure of astronomical bodies, and of cosmical matter in general, from the observations of the astronomer.

The ultimate object of cosmogony, and of the present book in particular, is to construct a sequence of pictures which will provide a contribution towards answering the questions of whence and whither by revealing the past and future of the ever-changing universe. But before attacking the main problem we must study the physical constitution of the bodies with which we are dealing, and as a preliminary to this we shall survey the universe revealed by observational astronomy. Cosmical physics will occupy the first five chapters of our book, but the present chapter will merely describe the picture which observational astronomy provides—for cosmical physics to interpret, and for cosmogony to extend into the past and future.

THE SOLAR SYSTEM.

2. In the foreground of the picture we must place our own solar system. A cursory study of the sky shews that the great majority of the stars retain their positions unchanged relative to one another, at any rate through times far greater than the lives of individual men. None of us will ever see the stars of the Great Bear or of the belt of Orion change their relative positions to any appreciable extent. But against the background provided by this unchanging framework of stars, certain other bodies move with such rapidity that their changes may often be noticed from day to day: these are the planets or wanderers. Like the earth, they describe orbits around the sun. The orbits of these planets and of the earth are approximately circular; all lie approximately in one plane, and all are described in the same direction about the sun. The motion of the planets as they describe their nearly circular orbits, relative to the earth which is itself describing another nearly circular orbit, accounts for the apparently intricate motions of the planets in the sky.

Some sixty-six years after Copernicus had put forward this interpretation of the observed planetary motions, Galileo turned his newly-made telescope on to Jupiter and observed four satellites revolving around it in precisely the way in which Copernicus had maintained that the planets revolved around the sun; all their orbits were nearly circular, all were nearly in one plane, and all were described in the same direction around Jupiter. This provided direct visual proof that the Copernican interpretation of the solar system was tenable and even plausible; many found in it a final and convincing proof of the truth of Copernican theories.

But in verifying Copernicus' solution of one problem Galileo had opened up another deeper and more fundamental problem. For there were now seen to be at least two systems of almost exactly similar structure in the universe, and it was natural to conjecture that similar causes must have been at work to produce two such similar effects. In this way scientific cosmogony had its origin, although nearly two centuries were to elapse before much serious thought was devoted to it.

Modern astronomy has shewn that the similarity between the systems of Jupiter and the sun is far more pronounced than was known to Galileo; actually Jupiter has nine satellites whose general arrangement with respect to Jupiter bears a fairly close resemblance to that of the eight planets in respect to the sun. Moreover, the system of Saturn, again with nine satellites, provides a further instance of precisely the same formation. Not only so, but in addition to the eight great planets, the sun is surrounded by some thousands of minor planets or asteroids*, whose orbits shew the same general regularity as has been already noticed in the motions of the great planets. Some, it is

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* Up to the end of 1927, 1069 of these were definitely identified with numbers and names, while the discovery of about 1200 others had been reported.

true, have substantially greater inclinations and eccentricities than are found among the great planets. For instance, the planet whose orbit has the greatest inclination to the general plane (invariable plane) of the solar system is Mercury with an inclination of 7° 0′; against this the orbit of the minor planet Pallas has an inclination of 34° 43′, and that of Hidalgo an inclination of 43°. The planet whose orbit shews the greatest eccentricity is Mercury, with an eccentricity of 0·206, whereas the minor planets Albert and Hidalgo have eccentricities of 0·54 and 0·65 respectively.

But the outstanding fact remains that all the orbits are described in the same direction. Adopting an argument which Laplace advanced in his *Système du monde* (1796), we may remark that if the directions of motion of 2000 planets and minor planets were a matter of pure chance, the odds would be $2^{1999} - 1$ to one against the coincidence of the orbits being all described in the same direction. Thus the odds that the directions of the orbits are *not* a matter of pure chance, are far greater than those in favour of well-attested historical events: it is more certain that some definite cause underlies the directions of motion in these orbits than it is, for instance, that the Athenians won the battle of Marathon, or that Queen Anne is dead.

The motion of the satellites of the planets continues, on the whole, the story of ordered arrangement already told by the motions of the planets, although here certain definite exceptions must be noted. These exceptions are limited to the outermost edges of the solar system and the outermost edges of the systems of Jupiter and Saturn. They are as follows:

Neptune, the outermost planet, has only one satellite, and this moves with retrograde motion—i.e. in the direction opposite to that in which Neptune and the other planets move round the sun.

Uranus, the next outermost planet, has four satellites, all moving in the equatorial plane of the planet, which is highly inclined to the general plane of the solar system.

Saturn, which comes next, has nine satellites, the outermost of which (Phoebe) revolving at a mean distance of 217 diameters of Saturn, moves with retrograde motion.

Jupiter has nine satellites, the two outermost of which move with retrograde motion.

THE DISTANCES OF THE STARS.

The nearer Stars.

3. The solar system has occupied the foreground of our picture of the universe, because its members are incomparably nearer to us than other astronomical bodies. As a preliminary to filling in the rest of the picture let us imagine the various objects in the universe arranged in the order of their distances from the earth. Disregarding bodies much smaller than the earth,

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such as the moon, other planetary satellites and comets, we must give first place to the planets Venus and Mars, which approach to within 26 and 35 millions of miles of the earth respectively. Next in order comes Mercury with a closest approach of 47 million miles, and then the sun at about 93 million miles. Other planets follow in turn until we reach Neptune at a distance of 2800 million miles.

After this comes a great gap—the gap which divides the solar system from the rest of the universe. The first object on the far side of the gap is the faint star Proxima Centauri, at a distance of no less than 25,000,000 million miles, or more than 8000 times the distance of Neptune. Close upon this come the two components of the binary star α Centauri at 25,300,000 million miles; these, with Proxima Centauri, form a triple system of stars which are not only near together in the sky, but are voyaging through space permanently in one another's company. After these come three faint stars, Munich 15,040, Wolf 359, and Lalande 21,185, at 36, 47 and 49 million million miles respectively, and then Sirius, the brightest star in the sky, at 51 million million miles. Comparing these distances with the distances of the planets, we see that the nearest stars are almost exactly a million times as remote as the nearest planets.

A simple scale model may help us to visualise the vastness of the gulf which divides the planets from the stars. If we represent the earth's orbit by a circle of the size of the full stops of the type used in this book (circles of a hundredth of an inch radius) the sun becomes an entirely invisible speck of dust and the earth an ultra-microscopic particle a millionth of an inch in diameter. On this same scale the distance to the nearest star, Proxima Centauri, is about 75 yards, while that to Sirius is about 150 yards. We see vividly the isolation of the solar system in space and the immensity of the gap which separates the planets from the stars.

Before parting from this model, let us notice that the distance of one hundred million light-years to the farthest object so far discussed by astronomy is represented on the same scale by a distance of about a million miles. In this model, then, the universe is millions of miles in diameter, our sun shrinks to a speck of dust and the earth becomes less than a millionth part of a speck of dust. The inhabitant of the earth may well pause to consider the probable objective importance of this speck of dust to the scheme of the universe as a whole.

4. The ancients were, for the most part, entirely unconscious of the enormous disparity in size between the earth and the rest of the universe. But those few who urged that the earth moved round the sun, saw that this motion must necessarily cause the nearer stars to change their positions against the background provided by the more distant stars, just as a child in a swing observes near objects moving against the distant background of hills

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and clouds; they also saw that the extent of this motion would make it possible to estimate the distances of the nearer stars. Aristarchus of Samos, who anticipated Copernican doctrines as far back as the third century before Christ, explained clearly that motion of this kind must be observed unless the stars were very remote indeed, and, as no such motion could be detected, laid great stress on the extreme distances of the stars. Four centuries later Ptolemy argued that the impossibility of detecting such motion proved that the earth could not be in motion relative to the stars, and must therefore constitute a fixed centre around which the whole universe revolved. When the Ptolemaic doctrine was finally challenged by Copernicus and Galileo, it became important to detect motion of the kind we have described, both as providing final and conclusive proof that the earth was not the unmoving centre of the universe, and as giving evidence as to the distances of the stars.

The apparent motion caused by the swing of the earth in its orbit is described as parallactic motion; the half of the angle swept out by a star as the earth moves from one extremity of its orbit to the other (or the angle from the mean position to either extreme) is called the "parallax" of the star. A star whose parallax is one second of arc is at a distance at which the mean radius of the earth's orbit subtends an angle of one second of arc. This distance was first introduced as a unit for the measurement of stellar distances by Kobold, and was subsequently named the "parsec" by H. H. Turner. Since there are 206,265 seconds of arc in a radian, the actual length of the parsec is 206,265 times the mean radius of the earth's orbit. The mean radius of the earth's orbit, commonly called the "astronomical unit" being 92,870,000 miles, or 149,450,000 kilometres, the parsec is found to be 19,150,000 million miles or $3{\cdot}083 \times 10^{18}$ centimetres.

Long before the introduction of this unit Herschel had used as unit a quantity which he called "the distance of Sirius," and was supposed to represent the mean distance of "first magnitude" stars (cf. § 5). Seeliger gave precision to this unit, defining it as the distance corresponding to a parallax of 5 parsecs, or 1,031,324 astronomical units. Charlier and various other continental writers call this unit the Siriometer and define it to be 1,000,000 astronomical units or $14{\cdot}94 \times 10^{18}$ cms.

Another unit of astronomical distance, especially used in popular exposition, is the "light-year" or distance which light travels in one year. Since light travels $2{\cdot}998 \times 10^{10}$ cms. in a second, and there are 31,557,600 seconds in a year, the light-year is found to be equal to $9{\cdot}461 \times 10^{17}$ cms. or 5,880,000 million miles.

The relation between the three sets of units is as follows:

One parsec $= 3{\cdot}083 \times 10^{18}$ cms. $= 3{\cdot}259$ light-years.
One light-year $= 9{\cdot}461 \times 10^{17}$ cms. $= 0{\cdot}3069$ parsec.
One Siriometer $= 14{\cdot}94 \times 10^{18}$ cms. $= 4{\cdot}848$ parsecs.

5. Long before parallactic motion was detected, it had been clear that such motion must necessarily be of very small amount. Early in the seventeenth century Kepler had maintained that the stars were merely distant suns; if so, the enormous difference between the intensities of sunlight and starlight could only be explained by supposing the stars to be millions of times as distant as the sun. Newton* pointed out that Saturn appears as bright as a first magnitude star, although its size is such that it can only re-emit by reflection about one part in ten thousand million of the total light emitted by the sun, and deduced that "first magnitude" stars, by which he meant the twenty or so brightest stars in the sky, must be about 100,000 times as distant as Saturn. This would assign to them a distance of about 90 million million miles, representing a parallax of 0·21 seconds of arc. The estimate was not a bad one; actually the twenty brightest stars in the sky have a mean parallax of 0·134 seconds. Immediately after this Bradley attempted to measure the parallax of γ Draconis, and although he failed to achieve his primary aim, he proved conclusively that the star's parallax was less than a second of arc.

6. Not until 1838 was the great gulf definitely bridged; in that year Bessel, Struve and Henderson independently found unmistakable positive

Table I. *Stars within five parsecs of the Sun.*

	Star	Parallax	Distance in parsecs
1	Proxima Centauri	0·765	1·31
2	α Centauri	0·758	1·32
3	Munich 15040	0·538	1·86
4	Wolf 359	0·404	2·48
5	Lalande 21185	0·392	2·55
6	Sirius	0·377	2·65
7	B.D. −12°, 4523	0·350	2·86
8	11 h. 12·0 m., −57·2	0·340	2·94
9	Cordoba 5 h. 243	0·317	3·16
10	τ Ceti	0·315	3·17
11	Procyon	0·312	3·21
12	ε Eridani	0·310	3·23
13	61 Cygni	0·300	3·33
14	Lacaille 9352	0·292	3·42
15	Struve 2398	0·287	3·48
16	Groombridge 34	0·282	3·55
17	ε Indi	0·281	3·56
18	Kruger 60	0·256	3·91
19	0 h. 43·9 m., +4·55	0·255	3·92
20	Lacaille 8760	0·253	3·95
21	2 h. 50·3, +52·1	0·239	4·18
22	23 h. 59·5, −37·9	0·220	4·55
23	17 h. 37·0, +68·4	0·213	4·69
24	10 h. 14·2, +20·4	0·207	4·83
25	Altair	0·204	4·90
26	o_2 Eridani	0·203	4·93

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* *System of the World* (1727).

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parallaxes for the three stars, 61 Cygni, α Lyrae and α Centauri. It had at last been found possible to sound the depths of space and the universe lay open for exploration. As the result of the labours of many astronomers, the parallaxes of over 2000 stars are now known with high accuracy. In the great majority of cases the errors of the determinations lie well within a hundredth of a second of arc, which is the angle that a pin-head subtends at a distance of ten miles.

In Table I (p. 7) will be found a list of all the stars which are at present known to lie within a distance of 5 parsecs of the sun.

Density of Distribution of Stars.

7. There is no reason for expecting any special concentration of stars in the immediate neighbourhood of the sun. If our nearest neighbours in space are distributed approximately at random, the number of stars within a sphere of any radius drawn round the sun should be approximately proportional to the volume of the sphere, and therefore to the cube of its radius.

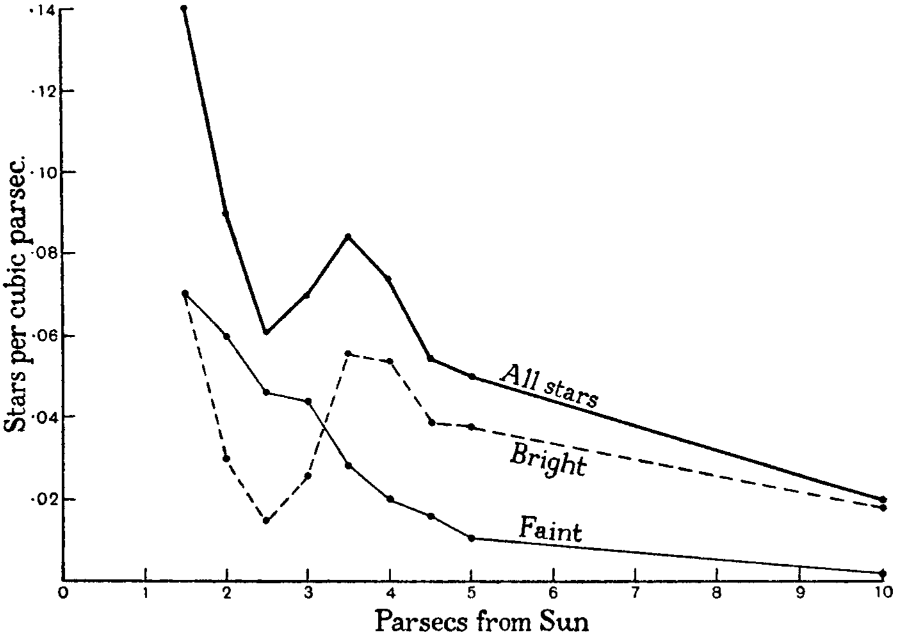

Fig. 1. Density of Distribution of known Stars in the neighbourhood of the Sun.

Fig. 1 shews the distribution of known stars in the neighbourhood of the sun. The abscissa measures distances from the sun in parsecs, while the ordinate gives the number of known stars per cubic parsec within this distance. The uppermost (thick) curve refers to the total of known stars of all kinds, the chain curve refers to stars which emit at least a thousandth

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part as much light as the sun, while the thin curve refers to stars which emit less than a thousandth part of the light of the sun (see Table IV, p. 33).

8. If all the stars were known we should expect the number of stars per cubic parsec to approach to a definite limit as we receded from the sun. The curves in fig. 1 shew no evidence of such a limit, so that we must conclude that nothing like all the stars in the neighbourhood of the sun are known.

Very faint stars can only be observed if they are quite near to the sun. Disregarding very faint companions of brighter stars, only six stars are known which emit less than a thousandth part of the light of the sun, and of these five are within 3 parsecs of the sun. This explains why the curve of faint stars runs down very rapidly after about 3 parsecs.

The brighter stars can be observed at greater distances. Actually the curye giving the density of bright stars shews no appreciable falling off up to a distance of about 4 parsecs, suggesting that practically all the bright stars within this distance are known. The curve suggests that the density of distribution of such stars is of the order of 0·05 stars per cubic parsec, or one bright star to every 20 cubic parsecs.

It is far more difficult to estimate the true density of distribution of the faint stars. To make a convenient figure for future calculations, we may suppose this to be the same as that for bright stars, so that the density of distribution of stars of all kinds near the sun is one to every 10 cubic parsecs, this requiring 18 stars actually to exist within 3½ parsecs of the sun, of which only 15 are known. These 18 stars are of course additional to the sun itself. In a statistical discussion such as the foregoing we must be careful not to count the sun in our statistics, since its presence is an essential to our being able to make the calculation at all. Our procedure is in effect to draw a small sphere round the sun and discuss the density of distribution of stars in the space bounded by this sphere on the one side and by a larger sphere of variable radius on the other.

Distant Stars.

9. We have seen that the direct method of parallactic measurement has only succeeded in surveying the universe with tolerable accuracy to a distance of about 3½ parsecs, or let us say 10 light-years, from the sun. No doubt this distance will be extended in time, but there is a natural limit to the power of the parallactic method. At best it can only measure the distance of a star whose parallactic motion can be projected on a background of far more distant stars, so that it must inevitably fail for the most distant stars of all. In actual fact it is bound to fail long before this.

The parallactic motion of a star at a distance of 100 parsecs, or 325 light-years, consists in the description of a circle or ellipse whose apparent size in the sky is that of a pin-head held at a distance of 5 miles. The apparent

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orbit of a star at a distance of 1000 parsecs, or 3250 light-years, is of course only a tenth as great; it is of the size of a pin-head held at a distance of 50 miles. The resources of observational astronomy are strained to the utmost to detect even the former of these parallactic motions, and are totally inadequate to measure it with accuracy, the error of measurement being about equal to the whole quantity to be measured. It is utterly impossible either to detect or measure the smaller parallactic motion of a star a thousand parsecs away, and is likely to remain so for many centuries to come. Yet a thousand parsecs is only a tiny fraction of the whole size of the universe. To survey the remote depths of space something of wider reach than the parallactic method is needed. Quite recently astronomers have discovered other and more far-reaching methods.

10. *Spectroscopic Parallaxes.* One of the most important of these is the method of "spectroscopic parallaxes" discovered by Dr W. S. Adams, now Director of Mount Wilson, and Kohlschütter in 1914. Two stars which are of exactly similar structure in all respects must necessarily emit light of precisely similar quality, so that their spectra must be similar in all respects. If the stars were at different distances, the spectra would naturally differ in brightness, and on measuring the ratio of their two intensities, it would be possible to deduce the ratio of the distances of the stars. Thus if the distance of one star had already been determined by the trigonometrical method already explained, it would be easy to deduce the distance of the other, even though this were so great as to render a direct determination of its parallax utterly impossible. The actual problem is generally far more complicated. When two stars have the same temperatures and the same chemical composition, their spectra are in general almost identical, but they shew minute differences if those parts of their atmospheres which emit their radiation are at different pressures. For reasons which will become clear later, stars of different sizes generally have different pressures in their atmospheres, and so exhibit slightly different spectra. Working backwards from this fact, Dr Adams discovered how to deduce the difference in size of two otherwise similar stars from minute differences in their spectra. As the difference in the intensity of their light arises jointly from differences in size and differences in distance, it is a simple matter to deduce the ratio of the distances of the two stars when once the ratio of their two sizes has been determined. This method is generally called that of spectroscopic parallaxes; it can hardly yet claim the accuracy of the trigonometrical method for near stars, but it has the great advantage of being successful with stars which are too remote for the trigonometrical method to be applicable at all. It is of course only of use for stars which appear moderately bright, but there is no limit to the distances at which it is available.

11. *Cepheid Parallaxes.* An even more far-reaching method of determining stellar distances depends on the peculiar properties of a certain class of stars