The Nebular Hypothesis & Modern Cosmogony

being

THE HALLEY LECTURE

Delivered on 23 *May*, 1922

by

J. H. JEANS

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AT THE CLARENDON PRESS
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I am indebted to Prof. G. W. Ritchey, Mr. Adrian van Maanen, and Mr. F. G. Pease, all of Mount Wilson Observatory, for permission to reproduce the photographs and diagrams which appear on Plates I–IV.

J. H. JEANS.

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THE NEBULAR HYPOTHESIS AND MODERN COSMOGONY

FROM among the innumerable scientific cosmogonies which have been propounded at various times, the nebular hypothesis of Laplace stands out as by far the most famous and the most lasting. The fame that it has achieved must be attributed to its intrinsic merits, for no blare of trumpets heralded its birth, and its author did nothing to endow it with the prestige of his great name; indeed, to judge from the manner in which it was announced, he seems to have felt somewhat apologetic for bringing it into the world.

In the very last of the fifty-one chapters which constitute his *Exposition du Système du Monde,* Laplace comments on the 'astonishing' circumstance that all the planets and satellites known to him[1] revolved in the same direction around their primaries. Such regularity, he remarks, cannot have resulted from mere chance—the odds against fortuitous causes producing such regularity are more than two milliards to one, and so are greater than the odds in favour of most of the universally accredited events of history. It is more certain that the regularity of motion in the solar system has a definite cause than it is certain, to choose our own instances, that the Greeks won the battle of Marathon or that Queen Anne is dead.

In this argument of the great French mathematician we have the birth of the science of cosmogony, the science which takes as its province the interpretation of the regularities observed in the formation and motion of the heavenly bodies. It is, perhaps, strange that it had

[1] Laplace, writing in 1796, appears to have been unaware that Herschel had discovered the retrograde motion of the Satellites of Uranus in 1787.

not come to life sooner, for the problem had been calling for solution ever since the true nature of the motions of the planets and their satellites had been established by Copernicus and Galileo. Various sporadic attempts had, it is true, been made, but one and all were still-born, each having some radical defect which made its further development impossible.[1]

We might perhaps expect that Laplace having demonstrated the existence of the problem so clearly, would devote a new volume, or at least a new chapter, to its discussion. But no: he merely remarks that in a final note to the current chapter he will propound an hypothesis which seems to him plausible, but which he puts forward 'avec la défiance que doit inspirer tout ce qui n'est point un résultat de l'observation ou du calcul'. This remark suggests an explanation of the otherwise surprising fact that the most eminent mathematician in France and the greatest astronomer of his age should feel so little interest in the causes underlying those planetary motions on which he was the supreme authority. Observation and calculation, still the principal weapons in the armoury of the scientist, were for Laplace the only ones; facts and deductive reasoning constituted the whole of science, and the day of inductive reasoning was yet to dawn.

On turning to 'Note VII et dernière', we find that the exposition of the hypothesis occupies but little more than a thousand words; we will attempt a summary, but the original is so brief that there can be but little difference between a summary and a verbatim reproduction. Laplace begins by conjecturing that the only cause capable of making the directions of motion of all the planets conform to that of the sun's rotation must have been a fluid of enormous extent, which surrounded the primaeval sun like an atmosphere and rotated with it, so that in its earliest

[1] Laplace states that he knows of no one except Buffon who had considered the problem at all; he appears to have been ignorant of the hypotheses of Kant (1755), Thomas Wright (1750, quoted by Kant), Swedenborg (1734), and Descartes (1644).

stages the system would appear from outside like a diffuse nebula with a stellar nucleus. A multinuclear nebula, he suggests, must, in consequence of gravitational condensation, evolve into a group of stars of precisely this type: the Pleiades are instanced as a probable illustration.

Laplace next reminds us of certain theoretical results which he has given in a previous chapter. The atmosphere of a rotating star cannot extend indefinitely; it is necessarily limited by a surface formed by the series of points at which centrifugal force exactly balances gravity. Now, as a star cools, and its outer layers condense and contract, its speed of rotation must continually increase, as is shown by the principle of areas (conservation of angular momentum). Consequently the limiting surface must move ever nearer and nearer to the axis of rotation. If we suppose, 'as is natural to admit', that the sun's atmosphere, in some past epoch, extended right up to this limiting surface, then the contraction of the surface in subsequent epochs must have resulted in successive sheddings of rings of molecules as they found themselves left outside the contracting surface.[1] Out of this shed matter Laplace supposes the planets to have been formed by a process of gravitational aggregation.

Leaving Laplace and the eighteenth century behind us, let us attempt to examine the nebular hypothesis in the light of the accumulation of knowledge which has since been gained—on the observational side by the labours of a whole army of astronomers equipped, in these latter years at least, with an array of instruments and methods that would have seemed like fairy-tales to Laplace, and, on the theoretical side, by the researches of some of the most eminent mathematicians of the nineteenth century, including, to mention only four, Jacobi, Kelvin, Poincaré, and Sir George Darwin.

If only our mathematical knowledge were adequate to the task, the theoretical test would be the more searching. But it is not adequate. The knowledge required is that of

[1] Laplace produces no argument to show that the limiting surface must contract more rapidly than the surface of the star.

the chain of configurations which will be assumed in turn by a mass of rotating gas collapsing slowly as the result of its emission of radiation, and this problem is still far from fully solved. Even the solution of the much easier problem in which we limit our attention to an ideal mass of absolutely homogeneous and uniform matter remains incomplete. It is, moreover, known that an ideal mass of this kind does not provide a fair analogy to the behaviour of a real astronomical nebula.

As regards the observational test, Laplace may perhaps have cherished a hope that the increasing power of astronomical instruments would in time reveal a whole chain of formations in the sky, forming an evolutionary sequence beginning with gaseous nebulae and ending with systems similar to that of our sun with its family of planets. He himself indicated the system of Saturn with its rings and planets as a probable type of formation to be expected on this chain. This hope has not been fulfilled. Observation has revealed a great variety of formations in the sky, but none similar to Saturn, and none which seems capable of being fitted on to the supposed chain connecting gaseous nebulae with solar systems. The observational test, however, is not destructive, it is merely inconclusive. Our most powerful telescopes are still inadequate to exhibit the stars as anything more than mere points of light, and if every star in the sky were surrounded by rings like those of Saturn or encircled by planets like those of our sun, we should still be totally unable to observe either a single ring or a single planet.

Happily the deadlock is not so complete as might be thought. There exist in the sky bodies of a size incomparably grander than the stars—the nebulae. These bodies do not appear as points of light: on the contrary, many of them appear so large that we can study their minutest details. About half a million of these giant formations appear to lie on a continuous evolutionary chain. At one end of this chain, we believe, are masses of rotating shrinking gas of precisely the type imagined by Laplace.

It is of this evolutionary chain that I propose primarily to speak to-day, in the belief that the study of the formations on this chain provides us with the fullest answer at present available to the problem propounded by Laplace.

Abstract mathematical theory shows that a mass of gas or other fluid matter in slow rotation must assume the shape of an oblate spheroid—a figure which possesses an equatorial bulge like our earth and for precisely the same reason. A ship on the earth's equator is farther from the earth's centre than it would be at either of the poles, and,

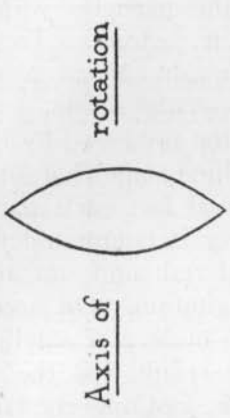

FIG. 1.

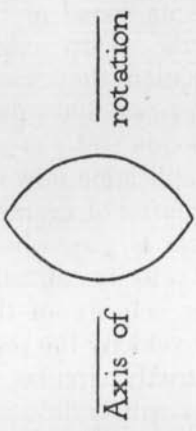

FIG. 2.

if the earth's rotation were suddenly stopped, would start 'down-hill' towards the poles. In the actual event, ships, oceans, and continents would all readjust themselves until the equatorial bulge had completely disappeared and the earth had assumed a spherical form. In the same way, if the earth's speed of rotation were increased, the equatorial bulge would become accentuated, and within limits any increase of rotation could be compensated by a suitable increase in the eccentricity of the spheroid. In the case of a nearly incompressible mass such as our earth, this remains true up to quite high degrees of eccentricity of the spheroid. But the case of a highly compressible mass such as a gaseous nebula is different, in that the spheroidal shape is soon departed from. Even for moderate rotations the equatorial bulge is much sharper and more clearly defined than on a spheroid, and at a certain critical speed of rotation the bulge develops into an actual sharp edge, so that the figure of the mass of gas becomes similar to that of a double-convex lens with a perfectly sharp edge (cf. Figs. 1 and 2[1]). When this particular speed of rotation is reached, no possible adjustment of figure can compensate a further increase of speed. All along the sharp edge the effect of centrifugal force is just, and only just, balanced by gravity, and if the main mass shrinks further and so increases its speed of rotation, the particles which constituted the sharp edge are left behind. To a first approximation they may be thought of as a ring of infinitesimal satellites describing circular orbits.

The motion so far is precisely that predicted by Laplace, but a complication now ensues which somewhat alters the further course of events. In actual fact each particle is a molecule of gas, whose velocity is compounded of its circular velocity already considered and its ordinary molecular velocity of thermal agitation. On account of the latter velocity the paths of the molecular satellites will not be strictly circular, with the result that the various molecules will collide at intervals, not merely with one another, but also with the molecules in the contiguous inner ring of matter. In this way there must be a continual interchange of momentum between the outermost and the next inner ring of molecules. Now this molecular interchange of momentum is precisely the mechanism of the action of gaseous viscosity, and every physicist will see at once that it will result in a tendency for the angular velocities of the two rings of molecules to equalize. At present they are not equal, for the inner mass will have shrunk since the shedding of the outer ring of molecules, and so will, in accordance with the principle of conservation

[1] Fig. 1 is drawn for an ideal extreme case of adiabatic equilibrium with γ (the ratio of the specific heats) equal to $2\frac{1}{6}$. Fig. 2 is drawn for the similar case with $\gamma = 1\frac{1}{5}$. It is believed that all lenticular figures occurring in nature are likely to lie between these two extremes.

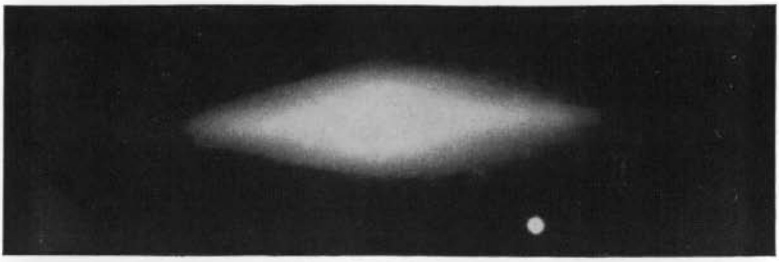

Fig. 3. N.G.C. 3115

Fig. 4. N.G.C. 5866

Fig. 5. N.G.C. 4594

Fig. 6. N.G.C. 4565

of angular momentum, be rotating faster than the outer ring. Thus the equalizing action of viscosity will make the outer ring rotate faster than its original speed, which was that appropriate to circular orbits, and it is a simple problem in orbital dynamics to show that this speeding up of the rotation will cause the ring, as a whole, to expand. It is not merely shed and left rotating in position, as Laplace imagined; rather will it appear to be thrown off into space, expanding as it rotates.

To trace the subsequent motion in detail is a task which has so far proved beyond the powers of the mathematician. If we assume the viscous action I have just described to be of sufficient potency to predominate over all other actions, then it is easily shown that the whole system, both ejected matter and central mass, would rotate with uniform angular velocity, and that the orbits of the ejected matter would be equiangular spirals. But, so far as our present knowledge goes, it is hardly justifiable to assign such a preponderating importance to this viscous action, and in any case it is probably better that we should study what observation shows actually to happen, than that I should give you further mathematical abstractions as to what might happen.

The lenticular figures shown in Figs. 1 and 2 represent the farthest stage of development to which theory can carry us with any certainty. Fortunately, just as theory fails, observation steps in to carry on the story. Fig. 3 shows an observed nebula, which would appear *prima facie* to be a material example of the lenticular figure predicted by theory. If this identification is accurate the nebula must be rotating about its smallest axis, and the next stage in its evolution ought to be the ejection of matter from its sharp edge. This particular nebula is so remote and so faint that it is impossible to test it for rotation, and its evolution is so slow that we cannot wait to watch what is going to happen next. But according to all indications it forms one of the half-million or so of objects, to which I have already alluded, which appear to fall into a single evolutionary chain. When we pass one stage along this chain we come to bodies such as that shown in Fig. 4, in which there is at least a suspicion of matter being thrown off from the equatorial sharp edge. A still farther stage brings us to Fig. 5, and here our suspicions receive confirmation, for the dark belt surrounding the central mass is most naturally interpreted as ejected matter which has darkened as a result of cooling. What is still more significant is that this nebula is known from indisputable spectroscopic tests to be in rotation about an axis at right angles to this ring—indeed, it has the special distinction of having been the first nebula in which rotation was detected.

A farther journey along the chain brings us to figures such as that shown in Fig. 6. Now there can be but little doubt that this is merely a 'spiral' nebula seen edgewise. Could we look at this nebula along its axis, instead of along a line of sight at right angles to its axis, we should probably find it to be a fairly typical spiral of the familiar kind shown in Figs. 7 and 9. Indeed, did time permit, I could easily bridge over this gap by showing you a whole series of nebulae changing continuously in appearance from Fig. 6 to Figs. 7 and 9, the change arising, so far as we know, merely from different orientations of the nebulae relative to the line of sight. Although there is but little doubt about this last step, it may nevertheless be frankly conceded that in connecting up our final figures with our original theoretical Figs. 1 and 2 we have to some extent been groping in the dark. If, and only if, we have not stumbled off the path, the bodies shown in Figs. 7 and 9 must have evolved out of rotating masses of gas.

On studying these figures our theoretical preconception that the ejected matter ought to form expanding circular rings of gas receives something of a shock. In these and thousands of similar nebulae, what we must regard as the ejected matter is found to lie along two curved arms, whose shape on exact measurement is found to be that of equiangular spirals. It is true that certain nebulae are known—one is illustrated in Fig. 8—in which the ejected

II

FIG. 7. M. 51 (N.G.C. 5194–5)

FIG. 8. N.G.C. 7217

matter might be regarded as lying very approximately in circular rings, but these are rare and abnormal; the more normal type illustrated in Figs. 7 and 9 exhibits two similar arms lying along equiangular spirals of moderate angle.

It is natural at this stage to reconsider the theoretical argument which led us to expect that the ejected matter would form a series of expanding rings. Upon review it is noticed that the argument assumed ideal conditions in which our rotating mass was supposed to have a whole universe to itself. Under actual conditions it is quite certain that other bodies must be present, and the gravitational attraction of these must of necessity exert tidal forces on the rotating mass which is primarily under consideration. If these other bodies are remote, the tidal forces will be small; if they are near, the tidal forces will be large. But, whether the tidal forces are large or small, it can be shown that their effect will be to localize the ejection of matter at two opposite points on the sharp equatorial edge of the mass, so that our original conception of expanding rings of gas must now be replaced by one of extending filaments of gas. Having gained this point of view we are in a position to understand another peculiarity of the spiral nebulae. It can be shown that a long continuous jet of compressible matter issuing from a source could not remain of uniform line-density. A configuration of uniform density would be unstable, and the jet would tend to form condensations or nuclei around which the whole of the matter of the jet would aggregate. Thus the appearance of the filament issuing from the nucleus of the nebula ought to be somewhat similar to that of a jet of water issuing from a fine nozzle and breaking up into separate drops, although the underlying mechanism in the two cases is totally different; such an appearance is observed in almost all spiral nebulae.

These considerations certainly leave us quite free, to put it no higher, to entertain the hypothesis that the nebulae shown in Figs. 7, 8, and 9 represent stages in the evolution of masses of rotating gas, and the common characteristics of the spiral nebulae as a class—the lenticular central nucleus, the two spiral arms proceeding from opposite points of this nucleus, the general similarity of these two arms, the tendency for the arms to break up into nuclei and condensations, all admit of simple explanation in terms of this hypothesis. The characteristic curve of the arms, which is an equiangular spiral, has not so far received any very convincing explanation, although it is possible that the action of gaseous viscosity, to which I have already referred, may provide a clue.

So far our discussion has been based solely on abstract reasoning and a study of a series of photographs of nebulae. The crucial question of actual fact still remains. In a real spiral nebula, as, for instance, that shown in Fig. 9, is the nucleus rotating, and is the matter of which the arms are formed being thrown out of this central nucleus? A telescope of infinite power would give us the answer in a moment.

Fortunately, although we cannot command the services of such a telescope, we have at our disposal two photographic plates of this particular nebula taken by the same telescope under similar circumstances, at an interval of eleven years, and these provide an adequate answer. Mr. van Maanen, of Mount Wilson Observatory, finds that the two plates are not identical; there is distinct evidence that the nebula has changed in the eleven years between the two exposures. He has selected 104 points in the nebular arms and measured their changes in the interval. The result is shown in Fig. 10, in which the arrows are each over one hundred times the measured displacement, being drawn to represent the motions of the selected points in 1,300 years. When the quantities to be measured are on so minute a scale a great deal must be allowed for errors of measurement. But on averaging over a large number of measurements, individual errors of measurement tend to destroy one another, while the true motion remains. As the result of a discussion of his measurements, Mr. van Maanen is able to announce, with

III

Fig. 9. M. 81

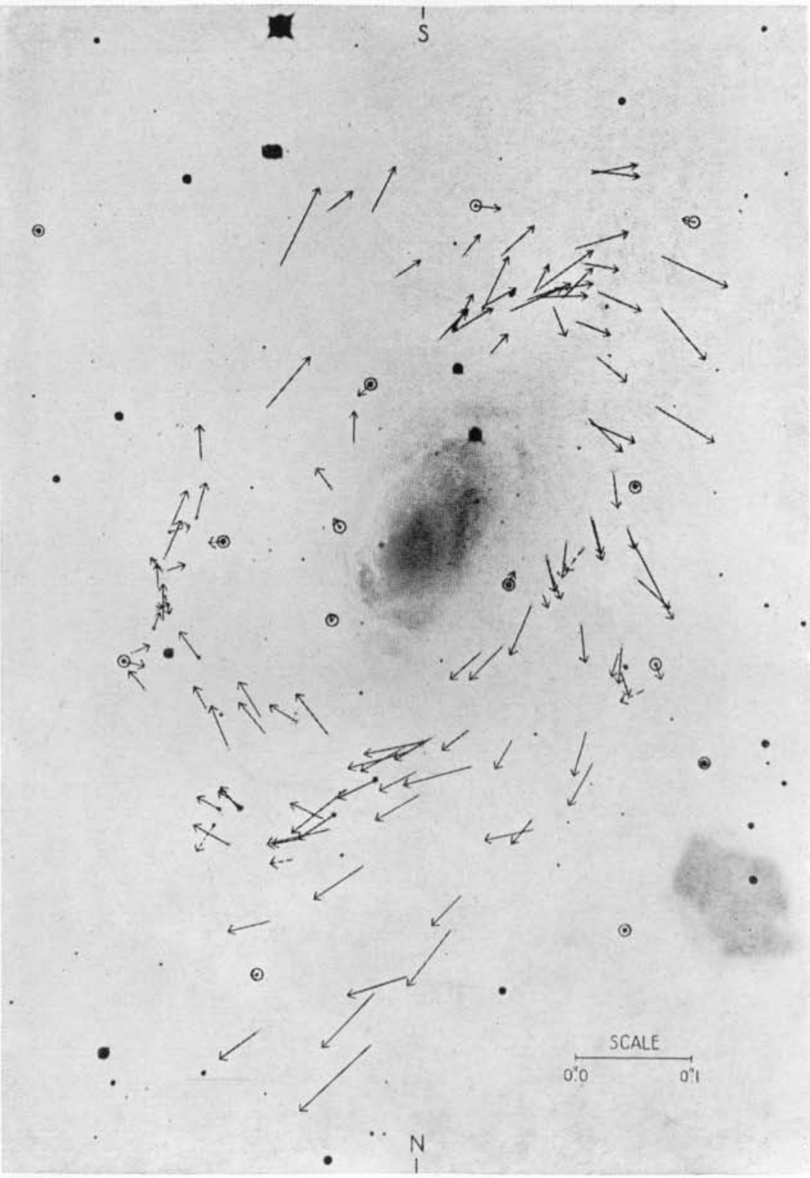

FIG. 10. INTERNAL MOTIONS IN M. 81

[The arrows indicate the direction and magnitude of the mean annual motions. Their scale (0".1) is indicated on the illustration. The points surrounded by circles represent stars which do not form part of the nebula.]

very fair certainty, that the motion of his selected points, as a whole, is along the arms in the direction away from the nucleus, showing that the arms are being continually emitted by the nucleus. Precisely similar motions have been observed by the same method in the arms of a number of other nebulae.

In all these nebulae the central nucleus is merely a confused mass of light in which it is impossible to identify individual points. For this reason no comparison of photographs can ever enable us to say whether the nucleus is rotating or not. But spectroscopic methods are available, and have established that the nuclei of a large number of nebulae are in rotation about axes at right angles to the planes of the nebulae. It is not possible to test all nebulae for rotation, but in no single case in which the test is possible is there the slightest ground for suspicion either that the nucleus is not rotating at all, or that it is rotating about any axis other than that which our theory would indicate, namely, the axis at right angles to the plane of the nebula.

Thus there seems to be very strong observational justification for the general statement that the nuclei of the spiral nebulae are rotating and are ejecting the spiral arms. Remembering that theoretical considerations predict that a rotating mass of gas ought, in due course, to assume a shape very similar to that assumed by the nuclei of the spiral nebulae, and ought to eject arms very similar to the observed spiral arms, the hypothesis that the spiral nebulae represent a normal stage in the evolution of a rotating mass of gas begins to appear quite reasonable—indeed, we may almost claim that it is something more than an hypothesis.

In the particular nebula (M. 81) shown in Figs. 9 and 10, Mr. van Maanen finds that the time required for a condensation in one of the arms to describe a complete revolution about the central nucleus is about 58,000 years. He has also measured the corresponding period for three other nebulae, with the results shown in the following table:

Nebula.	Period of Revolution.
M. 51	45,000 years
M. 81	58,000 „
M. 101	85,000 „
M. 33	160,000 „
Average of four:	87,000 years

An interesting conclusion emerges from these figures. In no nebula known does either arm describe more than two, or at most two and a half, complete revolutions around the nucleus, so that if the figures just given are at all typical of the majority of nebulae (and there is no reason to suppose they are not) we cannot escape the inference that all the matter we observe in the arms of the spiral nebulae must have been emitted from the nuclei in the last 200,000 years or so. But such a period can only be a mere moment in the life of a nebula, and we are driven to conclude that out beyond the visible arms of the nebulae there must be invisible arms containing the ejections of previous millions of years. The central nucleus throwing off its luminous nuclei as it rotates is a giant 'Catherine-wheel' firework throwing off sparks, but for each spark that we see there must be hundreds or thousands previously thrown off, which, after a brief period of luminosity, have lapsed into darkness.

The central nucleus of the average nebula, to the best of our knowledge, has assumed a lenticular shape and is emitting matter from the periphery of the lens, the period of rotation being of the order of 87,000 years. It is a mere matter of calculation to show that the mean density of this nucleus must be about 4×10^{-17} grammes per cubic cm. Judged by terrestrial standards this density appears amazingly low, but there are still about a million molecules to the cubic centimetre, and the mean free path of each molecule, about 2,000 kms., is only an infinitesimal fraction of the diameter of the nucleus.

The spiral nebulae are, without exception, so remote that a determination of their distances by direct (parallactic) methods is out of the question. In the case of one, and so far only one, nebula (M. 33 in Triangulus) it has been found possible to determine the distance by indirect means. In this particular nebula the velocity of rotation in kilometres per second can be found by spectroscopic observations, while the period of rotation in years has been found by the method already explained. Combining these two data, van Maanen has deduced that the distance of the nebula must be about 2,000 parsecs (6,000 light-years) and the diameter of the whole nebula about 100 light-years. The diameter of the nucleus is found to be about four light-years, while from the known period of rotation we can calculate that the mean density of the nucleus must be about 10^{-17} grammes per cubic centimetre. It follows that the mass of the nucleus must be of the order of 2×10^{38} grammes, about 100,000 times that of our sun.

You have no doubt noticed that the four periods of nebular notation tabulated on page 14 do not differ greatly from their average of 87,000 years; in no case is the difference represented by a factor as great as 2. If, for want of precise knowledge, we like to assume that the periods of rotation of *all* nebulae are of the order of 87,000 years, then we can at once perform calculations similar to that just given, for all nebulae whose velocities of rotation have been determined spectroscopically.

As an illustration, consider the most striking of all nebulae, the great nebula in Andromeda. Mr. Pease has found that the linear velocity of rotation at a point 2 minutes of arc from the nucleus is 58 kms. a second, and on assuming that the period of rotation is 87,000 years we can readily calculate that 2 minutes of arc must represent about $2\frac{1}{2}$ light-years, so that the distance of the nebula will be about 1,400 parsecs (4,200 light-years). The diameter of the nucleus, subtending about 12 seconds of arc in the sky, will be about 15 light-years in actual size, and as the assumed period of rotation of 87,000 years corresponds to a density of 4×10^{-17} grammes per cubic cm., it follows that the mass of the nucleus must be about 4×10^{40} grammes or about twenty million times that of our sun. It may be added that the error in this last estimate will be precisely the same as that in our estimate of the period of rotation; if this latter is double what we have assumed it to be, the mass will be just double what we have calculated it to be, and so on.

Whatever reasonable margin of error is allowed, it is clear at least that the spiral nebulae are structures of mass enormously greater than our sun. The evolution of these masses is not very different in its nature from the evolution of our sun as imagined by Laplace, but the scale on which it occurs is enormously greater. The primaeval nebula imagined by Laplace had a diameter about equal to that of the orbit of Neptune (10^{15} cm.); the visible part alone of the nebula in Triangulus (M. 33) has, as we have seen, a diameter 100,000 times this (10^{20} cm.); and that in Andromeda (M. 31) a diameter which is probably larger still. We naturally inquire whether the same process of evolution which we have studied in these gigantic nebulae can occur also on a relatively minute scale; would the forces of gravitation, rotation, &c., treat our primaeval sun in the same way in which, if our conjectures are sound, we see them treating the great nebula in Andromeda, and half a million others? If so, we shall clearly not need to go much farther to find the origin of the solar system.

As a preliminary to the consideration of this question, let me put before you still one further theoretical result. Mathematical theory, as we have already seen, predicts that condensations will form in the arms of a nebula; it also predicts how far apart these condensations will be. Now the mathematical expression for the mean distance between the condensations does not in the least depend on the properties of the central nucleus; it depends solely on the physical and chemical properties, namely, the molecular or atomic weight, density, and temperature, of the matter forming the arms. Thus, if we know, or can make a guess at, the temperature, density, and molecular or atomic weight of this matter, we can calculate the mean distances apart of adjacent nuclei.

The comparison of these calculated mean distances with the mean distances as they appear in the sky provides a second means of estimating the distances of the nebulae. By this method I estimated some years ago[1] that the distance of the great Andromeda nebula must be about 5,000 light-years, which is in satisfactory agreement with the estimate of 4,200 light-years we have just made by another method. A similar calculation led to an estimate of 3,000 light-years for the distance of the well-known nebula (M. 101) in Ursa Major, while in the same way we can estimate that the distance of the nebula (M. 51) shown in Fig. 7 cannot be more than about 500 light-years.

If we know these mean distances, and also the mean densities of the nebular arms, we can of course calculate the mean mass which will in time condense around each nucleus. The calculation leads to a highly significant result. In each of the nebulae we have had under consideration the mean mass of a condensation is found to be of the order of 10^{34} grammes, a mass which is comparable with that of the average star. Each of hundreds of thousands of similar nebulae appears to be shooting off masses of this magnitude into space at the rate of one every few years. Is it not, then, natural to suppose that, in watching the rotation of the spiral nebula, the emission of their spiral arms, the formation of nuclei in these arms, the aggregation of nebular matter round these nuclei, and the launching of these aggregations of matter into space, we are actually witnessing the birth of suns similar to our own? On this hypothesis we have an explanation of why the masses of the stars are what they are rather than, say, one-hundredth part or one hundred times this amount. The approximate equality of the masses of all stars can perhaps be traced back to an approximate equality of the periods of rotation of their parent nebulae, as suggested by the table on page 14, this in turn requiring an approximate equality in the densities of these nebulae, although

[1] Cf. *Problems of Cosmogony and Stellar Dynamics*, p. 217.

why these periods and densities should be so nearly equal remains at present unexplained.

Any attempt to trace the further life-history of these condensations—call them suns or stars if you like—brings us back at once to the question we have so far left unanswered. Each condensation, when it has escaped from its parent nebula, is initially a rotating and shrinking mass of gas, no longer of stupendous dimensions, but of size and mass just about comparable with those imagined by Laplace. Will the former process repeat itself in due course on a correspondingly smaller scale and result in the birth of an army of tiny bodies? No: for we have now seen that the mass of the bodies formed by the process in question will depend only on the physical and chemical properties of the parent nebula, not at all on its mass. To state it in terms of a concrete illustration, if nebula A is 100 times as massive as nebula B, all other things being equal, the stars born out of A will not be 100 times as massive as those born out of B; they will be merely 100 times as numerous and of the same mass. This theoretical result at once disposes of the possibility of the smaller members of the solar system having been born in the way we have been studying, but the same conclusion can be reached by a more direct path.

The smaller members of the solar system, as, for instance, our moon, the satellites of Mars, or the lesser satellites of Jupiter and Saturn, are at present devoid of atmospheres, and indeed, if atmospheres of ordinary gases were given them, they would be unable to retain them. The reason for this is not hard to understand. In any atmosphere each molecule is in flight with a velocity of the order of a kilometre a second, and in the outermost layer of the atmosphere the direction of flight of many molecules will be such as to carry them outwards into empty space. When an atmosphere surrounds a massive planet the gravitational attraction of the planet is sufficiently strong to check the flight of the escaping molecular projectiles and bring them back into the atmosphere; but the gravitational attraction of a small planet is inadequate to do this, so that molecule after molecule flies off into space, and the whole atmosphere rapidly becomes dissipated away. Exact calculation enables us to fix the limits of mass and density which empower a planet to retain an atmosphere, and we find that bodies which have diameters less than about 1,000 km. and densities comparable with those found in the solar system could not retain an atmosphere if they were given one.

If these same bodies were suddenly changed into the gaseous state the strength of their gravitational fields would be diminished, so that they would be even less capable than now of holding an atmosphere. The outermost layers of gas would, one after another, play the rôle of an atmosphere in turn, and wander far off into space, until the whole mass had disappeared. Obviously, then, the small bodies of the solar system can never have existed in the gaseous state; they must have been solid or liquid from their birth, and it is quite impossible that they should have been formed initially as condensations in a Laplacian ring of gas.

Returning to our main problem, it can be shown that, when a nebula which is only of stellar mass begins to break up by throwing matter off from its equator, there can be formed neither a Laplacian ring of gas nor definite nebular arms, for the reason that the small amount of matter so thrown off will not have sufficient gravitational cohesion to condense into a single mass. Thus the individual molecules will continue to revolve, each as a separate satellite, around the central mass.

With continued shrinkage the density of the central mass will progressively increase until at last, when a certain critical stage is reached, a striking change is found to occur. The rotating mass acquires an entirely new capacity—that of adjusting its shape so as to compensate the effects of its shrinkage without throwing off more matter from its equator. The new mechanism of compensation is found in the appearance of a bulge in the cross-section of the equator, which now becomes slightly elliptical. Further shrinkage is compensated by increasing ellipticity, and the figure becomes approximately an ellipsoid of three unequal axes, the shortest axis coinciding with the axis of rotation. In time, however, a point is reached at which this method of compensation also fails; no further method of compensation takes its place, so that, from here on, no state of equilibrium is possible. At this stage cataclysmic motion ensues. Although the details of this motion are beyond the present scope of mathematical analysis, there can be but little doubt as to its general character. The first stage is known to consist in the formation of a furrow on the ellipsoidal surface of the star, this furrow lying in a cross-section which is parallel to the axis of rotation and not far distant from it; as the cataclysmic motion proceeds, the furrow

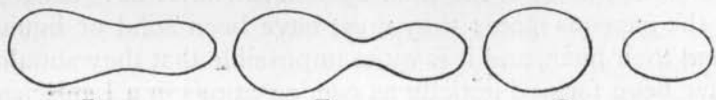

FIG. 11. FIG. 12. FIG. 13.

at first deepens. It seems highly probable, although this has not yet been rigorously proved, that the furrow will continue to deepen until it has divided the central mass of the star into two detached portions. The kind of motion which is conjectured to take place is shown in Figs. 11–13, the axis of rotation in each figure being parallel to the edge of the page.

When mathematical theory failed us on a former occasion, we were able to call upon observation to carry on the story. We may attempt the same procedure here, but we shall not meet with the same measure of success, for unfortunately we are now at a part of the evolutionary chain at which both theory and observation to a large extent fail together. No formation revealed by observation can be said, with any approach to certainty, to represent the theoretical configurations shown in Figs. 11 and 12, but Fig. 13 brings us back to the region of observed formations. The physical interpretation of this figure is quite simple; we have two separate stars revolving about their common centre of gravity, each always turning the same face to its companion. Now a considerable number of stars are known which are believed to have precisely this formation. They are too far away for their two constituents to appear as separate points of light, even in the most powerful telescope, but their binary nature is established either by peculiarities in their spectrum or by variations in their combined luminosity, and a technical discussion of these peculiarities shows that the two components rotate in circular, or very nearly circular, orbits about one another, their distance apart being so small that they are almost in contact. The well-known star β Lyrae is a typical member of this class.

These stars form members of a continuous series—the series commonly called 'binary stars'. As we pass along the series in one direction, the distance between the two components increases, until finally they can be seen telescopically as distinct points of light. Passing along the series in the reverse direction, the distance between the components diminishes until we come to stars such as RT Sculptoris and X Carinae, whose components are believed to be almost, if not actually, in contact, and farther still, to stars such as RR Centauri, of which the light variation is usually explained by the supposition that the two components 'overlap'. If our belief as to the evolutionary history of this and similar stars is correct, the configuration of RR Centauri will be somewhat similar to that shown in Fig. 12, in which case it is more accurate to say that the two components have not yet definitely formed than to speak of 'overlapping'.

The conjecture that the cataclysmic motion ends in fission rests on highly mathematical arguments, which it would be quite inappropriate to discuss here in detail; the best evidence I can put before you as to their general plausibility is that, so far as I know, no one has ever conjectured any end other than fission for this motion.

If the conjecture is accepted, the identification of the final product of cataclysmic motion (Fig. 13) with known binary stars of the type we have mentioned obviously rests on fairly solid ground. Before leaving it, perhaps I may mention a few further points of interest, which incidentally provide further justification for this identification.

We have already referred to a certain critical density, at which a rotating star can first assume an ellipsoidal figure. This critical density can be calculated, although not with any great accuracy because we are at present unable to make full allowance for the baffling effects of the pressure of radiation in the star's interior. If we disregard these effects altogether, we find that a star, if endowed with sufficient rotation, will first assume an ellipsoidal figure when its mean density is something like a quarter of that of water. There will be a further increase of density before the configurations shown in Figs. 11 and 12 are reached, so that, if pressure of radiation were not present to trouble us, we could be confident that the density of stars having these configurations would be greater than a quarter of that of water. But the effect of pressure of radiation is certainly to decrease this critical density, and is probably to decrease it by a very substantial amount. When allowance is made for this effect, it seems likely that the density of stars in configurations 11 and 12 will be somewhat less than a quarter of that of water, the exact density depending on the star's mass because the importance of pressure of radiation depends on the star's mass. Now the period of rotation which corresponds to a density equal to a quarter of that of water is about a day, whence we may conclude that, if stars actually exist in the configurations shown in Figs. 11 and 12, their periods of light variation must be of the order of 12 hours. Now the star RR Centauri, which we have taken as typical of stars in the configuration shown in Fig. 12, is found to have a period of light variation equal to only 7 hr. 16 min., corresponding to a period of rotation of 14 hr. 32 min.; the light period of RT Sculptoris is a few minutes over 12 hours, while that of X Carinae is somewhat longer, being 25 hr. 59 min. The same argument can be expressed, possibly in a more convincing way, in terms of spectral types. The theoretical critical density of one quarter of that of water is known to be reached by a star at just about that stage in its evolution at which its spectrum is of the special type known to spectroscopists as type *B*, and the vast majority of very close binaries are found to show spectra of type *B*.

It will be remembered that theoretical considerations led us to expect that a star, before assuming the ellipsoidal form, might probably be surrounded by an atmosphere consisting of the molecules which had been thrown off from the equator of the star while in its previous lenticular form. If the ellipsoidal star proceeds to fission in the way we have imagined, this atmosphere will no doubt in time resolve itself into two ordinary atmospheres surrounding the two components; but it is conceivable that traces of it, in its original form, may be found in stars in which fission has only just taken place. Now in certain stars of this type the larger and more massive star is found to be the darker. An instance is provided by our typical star β Lyrae, in which the larger star, with 2·2 times the mass of the smaller, gives only two-fifths as much light. This condition can be readily explained by the supposition of a cool outer atmosphere which has condensed mainly around the more massive constituent—an explanation suggested by Myers in 1898, long before it was suspected that such an atmosphere was required by evolutionary theory.

A definite peculiarity in the spectra of certain other stars suggests still more strongly that they are enveloped in an outer atmosphere of this kind. The spectrum of δ Orionis is for the most part of ordinary *B* type, the motion of the lines indicating that the light comes from two separate components revolving about one another with the high velocity of 200 km. a second in nearly circular orbits with a period of 5·732 days, the general indication being that the star has recently broken up by fission. But, as Hartmann and, more recently, Jordan have found, there is also a second spectrum which shows that a mass of cooler vapour containing calcium accompanies the star, and that this does not partake in the motion of either component, but moves with the steady uniform velocity of its centre of gravity. If the star δ Orionis were unique in the possession of this peculiarity we might reasonably suppose that the star happened to be partially hidden behind a cloud of calcium vapour, which in turn happened to be moving in space with just about the same velocity as the centre of gravity of the star. This at least would explain the observations, and was, in point of fact, the explanation originally suggested by Hartmann. But it has since been discovered that the same spectral peculiarity attaches to a great number of binary stars—all of them of *B* type, and all of them stars which in all probability have recently broken up by fission. We cannot reasonably suppose that all these *B*-type stars happen, by a remarkable coincidence, to have got partially hidden behind clouds of calcium vapour; we must rather suppose, as first suggested by Lee, that the calcium spectrum is caused by a true atmosphere which keeps its motion separate from that of the two stars it envelops. It accords well with evolutionary theory that evidence of such an enveloping atmosphere should have been found in the spectra of these newly-formed binary stars, the more so as it is possible to pass by continuous gradations to cases in which the enveloping atmosphere partakes partially but not wholly of the motion of the two constituents. Doubtless, could we trace the series far enough, we should find it ending in the complete attachment of the atmosphere to one or both of the two revolving stars, as it is suspected may have already happened in β Lyrae.

Without labouring the matter farther, it will be clear that there is enough circumstantial evidence to justify us in regarding fission into a binary star as the normal end of the cataclysmic process we have had under consideration. To obtain a full knowledge of the evolutionary chain right up to its end we have to discuss the question of what happens after fission. The answer appears to be: either nothing at all or more fission. When a star has broken in two parts by fission, each part is itself a new rotating and shrinking mass of gas, and it is possible that the fissional process may be repeated in either or both of the two components. Such further fission does not, of course, follow as a necessary sequence to the primary fission, for the two components may solidify, and so cease to shrink, before it occurs.

Russell, discussing the question theoretically, has shown that when repeated fission of this kind occurs, the distance between the two stars formed by a secondary fission must always be less than a fifth of the distance of the pair generated by the primary fission. The fact that multiple stars are generally formed of close and wide pairs is familiar to every practical astronomer, and may be verified by the merest glance at a catalogue of multiple stars, although, on account of foreshortening of the stellar orbits, the ratio of the distances of wide and close pairs as projected on the celestial sphere may not always appear to be as great as five to one. Russell, discussing this question statistically, finds that the apparent exceptions to the five-to-one rule agree, both in kind and in number, with what ought to be expected as a result of foreshortening. Thus, at the far end of the evolutionary chain both theory and observation are again at our service, and we find a gratifying concordance between the two.

We are now in a position to review the whole sequence of configurations on this chain. We started at one end of the chain with a mass of rotating gas, shrinking as a result of radiation and increasing its speed of rotation accordingly. We found that after a time such a mass would assume a lenticular shape and would then proceed to throw off matter from its equator. This is precisely the process imagined by Laplace, but the instances of it which we have observed in nature occur on a far more colossal scale than was thought of by Laplace. Up to this point, however, the scale is immaterial: Laplace's small mass would behave in precisely the same way as our observed large masses. But, from here on, scale is everything. If our gaseous nebula is of mass equal to a million suns, or something of this order of magnitude, it develops, we believe, into an ordinary spiral nebula. The ejected matter forms spiral arms, and then condenses around nuclei in these arms, until finally each separate nucleus forms a star. Each such star is initially a mass of shrinking, rotating gas, and the life-history of the parent nebula is reproduced in the child until the process of equatorial ejection of matter commences again. But now, on account of the smallness of the mass concerned, neither spiral arms nor condensations appear. The ejected matter merely forms an enveloping atmosphere; ultimately the central mass, continually shrinking, first assumes an ellipsoidal figure, and then, after cataclysmic motion, emerges as two distinct masses rotating about one another. The cool enveloping atmosphere gradually settles around the two stars until we are left with a normal binary star. No further evolutionary changes of a radical nature are to be expected unless one or both of the two constituents again breaks up by fission, in which case we are left with a triple or quadruple star of a type with which the practical astronomer is quite familiar.

This brings us to the end of the evolutionary chain. We have travelled its whole length and have not found what we set out to find—the solar system. If the whole aim of cosmogony were to discover the origin of our own system, our labour would have been in vain. But an intelligent cosmogony will have a more objective aim, and the cosmogonist will be concerned to gain a knowledge of the origins of the stars as a whole rather than of the genealogical tree of our own particular planet. Judged by the wider standard, Laplace's conception has been amazingly fruitful. It would hardly be too much to say that it has either revealed or given a valuable clue to the origin of every normal formation in the sky, with the single exception of that of the solar system which it set out to seek. But is the solar system a normal formation? The circumstance that it is not found on what we must now regard as the normal evolutionary chain would appear to cast grave doubts.

It will be remembered that in our discussion of the spiral nebulae we had to adjust Laplace's conceptions to actuality by taking account of the tidal forces emanating from other nebulae. Laplace's theoretical ideas were entirely correct, so long as they were treated merely as theoretical ideas; when applied to nature they failed, because Laplace had allotted a whole universe to each mass of rotating gas, and nature is not so lavish of her space.

Now our subsequent discussion of rotating stellar masses has in effect assumed these same ideal conditions—each star was treated as a self-contained world, and no allowance was made for the influence of its neighbours. There is, however, abundant evidence that the majority of stars have, sometimes in the course of their lives, been very extensively influenced by their neighbours. Mainly this evidence comes from a study of the orbits of binary stars. In a great many cases there is every reason to think that these stars owe their binary character to fission, but the vast majority of their orbits show evidence of something more than could be produced by fission alone—they indicate also the action, at some time after fission had occurred, of the disturbing influence of a passing star.

Naturally there is no reason why passing stars should specially select binary stars for their attentions. They must at times pass near also to single stars which have not broken up, and the tracing of the course of events on such an occasion forms a problem for the mathematician. If the wanderer does not pass very near, the only effect of his passage will be to raise a slight tide on the star whose fortunes we are following, and as he disappears the tide disappears too; the effect of the encounter has been merely transitory. But if the wanderer comes within a certain imaginary sphere drawn round our star, events of an entirely different kind may be expected. While he is still outside this sphere, he raises tides at two opposite points on the star's surface; as he approaches, these tides increase in height, until, when he finally enters within the magic sphere, two long arms shoot out from our star—one towards the wanderer and one in the exactly opposite direction. These arms are twisted out of shape by the gravitational pull of the passing star, and so assume a curved form. At the same time, another process is at work; since a uniform distribution of matter in the arms would not be stable, condensations form, around which the rest of the matter clusters. The final product will be a number of separate masses describing orbits about what is left of the original star. If these bodies are large, they may well remain gaseous; if they are smaller than a certain calculable size, they must be liquid or solid.

According to the tidal theory of the genesis of the solar system, we have been describing the birth of our earth and its sister planets. It would take too long to make a detailed comparison between the predictions of theory and the facts observed in our system. It may, however, be said in general that the type of system predicted by theory appears to have much in common with the system of our sun, although it ought in fairness to be added that further mathematical research, of a kind and amount which can only be described as terrifying, will be necessary before we can assert with any confidence that our solar system can be fully explained by this theory. If the tidal hypothesis may be provisionally entertained, then we may say that the solar system finds its place on the normal evolutionary chain, since it may be claimed that the normal event is for a star at some time in its career to be disturbed by the passage of a neighbour. The ideal conditions we assumed at first, in which each star lived its whole life without interference, were abnormal; they gave rise to a simple mathematical problem, but did not correspond to reality.

And yet a reservation must be made here. Although some disturbance from its neighbours must be the lot of every star, calculation shows that violent disturbance of the kind which tears off satellites will be the lot of only a very few. The vast majority of stars will experience nothing but transitory effects from the passage of other stars, and will end their lives, according to the amount of rotation with which they were initially endowed, as single, binary, or multiple stars, in every case without satellites. Systems such as our own must be rare in the sky: they may be normal in the sense that the events which formed the planets out of our sun might have happened to any star, but they are abnormal in the sense that such events have in all probability happened only to very few. Indeed, it is just within the bounds of possibility, although quite, I think, outside the bounds of probability, that our system is unique—that out of the two or three thousand million stars which people space, our sun may be the only one attended by satellites. To carry this train of thought one step farther, it is just possible, although again quite improbable, that our earth may be the only body in the whole universe which is capable of supporting life.

To the fundamental question of the meaning of human existence, astronomy has little of positive value to offer. It must be so, for the discussion of the question turns in the last resort on the ultimate significance of mind and matter. Astronomy knows nothing of mind and must perforce take matter for granted. But she can perhaps render some service in the humbler capacity of checking and criticizing the various conjectures which human thought has put forward as answers. The answers given by the human race in its infancy, the presumptuous answers which assumed in one form or another that terrestrial life was the sole reason for the existence of the myriads of stars in the firmament, met their death at the hands of Copernicus, an astronomer, and of Galileo, another astronomer. The arrogance of this view gave place to the humility of the succeeding view, which held that each of these millions of stars gave heat and light to families of planets peopled by living beings similar to ourselves, and of course quite as important as ourselves. But astronomy now seems to suggest that perhaps the pendulum has swung too far. We begin to suspect that life is not the normal accompaniment of a sun, since planets capable of sustaining life are not the normal accompaniments of suns. Astronomy does not know whether or not life is important in the scheme of nature, but she begins to whisper that it must necessarily be somewhat rare. Her suggestions, although still vague, seem to indicate that our terrestrial life forms a greater proportion of the sum total of all the life of the universe than we at one time thought.

It is perhaps well that I should end by stating explicitly what I hope has already been implied in my choice of language: that astronomy speaks with no certain voice on any of the subjects we have had under discussion. The big telescope at Mount Wilson can concentrate the light falling on 55 square feet of glass on to an area smaller than a pin point: in our enthusiasm at its power we are apt to forget how very much more power would be needed before it could give us any direct information about planets of the size of our earth attached to even the nearest of the fixed stars. The raw material of cosmogonical discussion is not astronomical observation, but inference from observation: the direct observation is of the slow motion of a spectral line through perhaps a thousandth part of a millimetre—the inference which the cosmogonist takes as his raw material is that we have to do with a binary star revolving in an orbit of so many kilometres diameter in so many hours. But any uncertainty that may attach to inferences of this kind is multiplied a thousandfold by the processes to which this raw material has to be subjected before the finished product is reached. The principal of these processes consists in blending the raw material with assumptions which from their nature are untested and of necessity untestable. We assume, for instance, that stellar matter at a temperature of 10,000,000° C. or at a density of 10^{-17} grammes per cubic centimetre obeys approximately the same physical laws as matter in our laboratories, we assume that action and reaction between the two gigantic constituents of β Lyrae is determined by the same laws as govern the fall of an apple to the ground, we assume a host of other things which need only be stated in words for their uncertainty to become manifest. And so it comes about that the cosmogonist can never be justified in stating the results of his investigations with any confidence; if he must make a positive assertion, the only one he is entitled to make is that in cosmogony we know nothing at all for certain.