The Origin of the Solar System.[1]

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THE astronomer of to-day has at his disposal telescopes which range in aperture from his naked eye, of aperture about one-fifth of an inch, up to the giant Mount Wilson telescope of more than 100 inches. If we lived in the midst of a uniform infinite field of stars, or in a field which was uniform as far as our telescopes could reach, the numbers of stars visible in different telescopes would be proportional to the cubes of their apertures.

In actual fact our naked eyes reveal about 5000 stars ; with a one-inch telescope this number is increased to about 100,000, with a ten-inch to 5 million, and with the 100-inch telescope to perhaps 100 million. These numbers increase much less rapidly than the cubes of the apertures. We conclude that we are not surrounded by an infinite uniform field of stars. We live in a finite universe, which thins out quite perceptibly within distances reached by telescopes of very moderate size. It is estimated that the whole universe consists of some 1500 million stars, our sun being not very far from the centre of the system.

Imagine the various celestial objects in this universe arranged according to their distance from us. Disregarding altogether bodies which are much smaller than our earth, we must give first place to the planets Venus and Mars, which approach to within 26 and 35 millions of miles respectively. Next comes Mercury with a closest approach of 47 million miles, and the sun at 93 million miles. The remainder of the planets follow at distances ranging up to 2800 million miles, the radius of the orbit of Neptune.

But now comes a great gap. The first objects beyond this gap are the faint star Proxima Centauri at a distance of 24 million million miles, or more than 8000 times the distance of Neptune, and close to it, α Centauri at 25 million million miles. Next in order come the faint red star Munich 15,040 at 36 million million miles, and another faint star Lalande 21,185 at about 47 million million miles. Thus our nearest neighbours among the stars are at almost exactly a million times the distances of our nearest neighbours among the planets. After these comes Sirius, the brightest star in the sky, at 50 million million miles.

From here on there is a steady succession of objects until we reach distances of more than 20,000 times that of Sirius; but long before these distances are reached other objects, spiral and spheroidal nebulæ, and ultimately star-clusters, are found to be mingled with the stars. The furthest object the distance of which is known with any accuracy is the star-cluster N.G.C. 7006, which Shapley estimates to be 25,000 times as distant as Sirius. This cluster is so remote that its light takes 200,000 years to reach us ; even for light to cross the cluster takes hundreds of years. To all appearances the star-cloud N.G.C. 6822 is still more remote. According to Shapley its distance is about six million million million miles, a distance which light takes a million years to traverse. So far as is known at present, this brings us to the end of our universe, or perhaps I ought to say it brings us back to the beginning.

It is no easy matter to get all these different distances clearly into focus simultaneously, but let us try. The earth speeds round the sun at about twenty miles a second ; in a year it describes an orbit of nearly six hundred million miles circumference. If we represent the earth's orbit by a pin-head or a full-stop of radius one-hundredth of an inch, the sun will be an invisible speck of dust, and the earth an ultra-microscopic particle one-millionth of an inch in diameter. Neptune's orbit, which encloses the whole of the solar system, will be represented by a circle the size of a threepenny-piece, while the distance to the nearest star, Proxima Centauri, will be about 75 yards and that to Sirius about 160 yards. On this same scale the distance to the remote star cluster N.G.C. 7006 is 2400 miles and that to the star-cloud N.G.C. 6822 about 12,000 miles, so that roughly speaking the whole universe may be represented by our earth.

It thus appears that we are on this occasion to discuss the origin and past history of a system which bears the same relation to the universe as a whole as does a threepenny-piece to our earth. Why are we so interested in this particular threepenny-piece? Primarily because, although a poor thing, it is our own, or at least one particle of it, one millionth of an inch in diameter, is our own. But there is a historical reason of a less sentimental kind. We have already noticed

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[1] Discourse delivered at the Royal Institution on February 15.

the immensity of the gap between our system and its nearest neighbours. As regards astronomical knowledge this gap has taken a great deal of crossing. Well on into last century, human knowledge of the further side of this gap was infinitesimal ; the stars were scarcely more than points of light, described as " fixed stars." In those days the problem of cosmogony reduced perforce to the problem of the origin of our own system.

Recent research has changed all this, and the modern astronomer has a very extensive knowledge of the nature, structure and movements of the various bodies outside our system. The cosmogonist of a century ago could assert that the solar system had evolved in such and such a way, and need have no fear of his theories being upset by comparison with other systems. But if I put before you now a theory of the origin of our system, you will at once inquire as to the behaviour of the 1500 million or so of systems beyond the great gap. Are they following the same evolutionary course as our
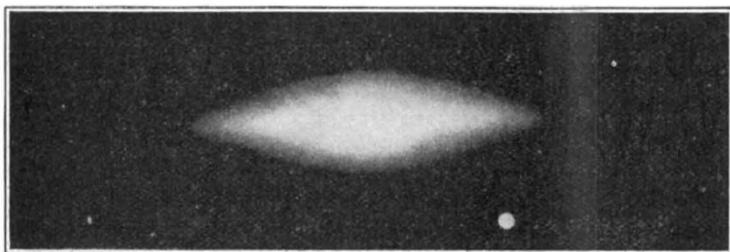

FIG. 1.—Regular shaped nebula (N.G.C. 3115).

own system, and, if not, why not ? It may be well to consider these other systems first.

Among these 1500 million or so of objects there are certain comparatively small classes the nature and interpretation of which are still enigmatical—the planetary nebulæ, the Cepheid variables, the long-period variables such as Mira Ceti, and a few others. Apart from these, practically all known bodies can be arranged in one single continuous sequence. The sequence is approximately one of increasing density : it begins with nebulæ of almost incredible tenuity and ends with solid stars as dense as iron. There is but little doubt that the sequence is an evolutionary one, for the laws of physics require that as a body radiates heat its density should increase, at least until it can increase no further. Let us begin our survey at the furthest point back to which we can attain on this evolutionary chain—the nebulæ.

After the enigmatical " planetary " nebulæ have been excluded, the remaining nebulæ fall into two fairly sharply defined classes, which may be briefly described as regularly and irregularly shaped nebulæ.

The irregularly shaped nebulæ comprise such objects as the great nebula in Orion, and the nebulosity surrounding the Pleiades. Until quite recently these irregular nebulæ were supposed to be of great evolutionary importance. It was noticed that they were usually associated with the very hottest stars : whence arose a beautifully simple cosmogony, asserting that these very hot stars were the immediate products of condensation of the nebulæ, and that their after-life consisted merely of a gradual cooling until they got quite cold. This cosmogony was too simple to live for long—it was buried some ten years ago by the researches of Russell, Hertzsprung, and others. Thanks to these researches, we now know that the very hot stars associated with irregular nebulæ, so far from being newly born, are standing at the summit of their lives awaiting their decline into old age.

A mass of hot gas isolated in space radiates heat, and this causes it to contract. If the mass radiated without contracting, it would, of course, get cooler ; on the other hand, if it contracted without radiating, it would get hotter. But when radiation and contraction are proceeding together it is not obvious without mathematical investigation which of the two tendencies will take command. In 1870, Homer Lane showed that a mass of gas of density low enough for the ordinary gas laws to be approximately obeyed, will in actual fact get hotter as it radiates heat away. Cooling does not set in until a density is reached at which the gas laws are already beginning to fail—that is to say when liquefaction and solidification are already within measurable distance. Thus we see that maximum temperature is associated with middle age in a star, the age at which the star may no longer be regarded as a perfect gas. At this period of middle age the surface temperature of the star may be anything up to about 25,000° C., while the temperature at its centre will amount to millions of degrees. Its average density will probably be something like one-tenth of that of water. It is still not known why stars at this special maximum temperature are so commonly associated with irregular nebulæ. Possibly it may be that only stars at the very highest temperatures are capable of lighting up surrounding nebulosity which would otherwise remain invisible. Be this as it may, it is fairly clear that these irregular nebular masses are not an essential part of the evolutionary chain. They are probably mere by-products, and as such may be dismissed from further consideration.

We turn to the nebulæ of regular shape. A great number of these appear as circles or ellipses, some as ellipses drawn out at the ends of their major-axes, sometimes almost to sharp points. An example of this last type of figure is shown in Fig. 1 (Nebula N.G.C. 3115).

A number of these regular-shaped nebulæ have been examined spectroscopically, and in every case have been found to be rotating with high velocities about an axis which appears in the sky as the shortest diameter of the nebula. The mathematician can calculate what configurations will be assumed by masses of tenuous gas in rotation. If rotation were entirely absent the mass would, of course, assume a spherical shape. With slow rotation its shape would be an oblate spheroid of low ellipticity—an orange-shaped figure like our earth. At higher rotations the spheroidal shape is departed from, the equator bulging out more and more until finally, for quite rapid rotation, the shape is approximately that of a double convex lens having a sharp circular edge for its equator, the shape, in fact, exhibited by the nebula shown in Fig. 1. The whole succession of figures, if looked at along all possible lines of sight, will exhibit precisely the series of shapes which are found to be exhibited by the regular nebulæ under discussion. There are, then, good grounds for conjecturing that these nebulæ are rotating masses of gas ; but we can test this conjecture further before finally accepting it.

As a mass of gas radiates its energy away it must shrink. If it is in rotation, its angular momentum will remain constant, and the shrunken mass can only carry its original dose of angular momentum by rotating more rapidly than before. This conception, which formed the corner-stone of the cosmogonies of Kant and Laplace, is still of fundamental importance to the cosmogonist of to-day. Thus every nebula, as it grows older, will rotate ever more and more rapidly and, barring accidents, will in due course reach the configuration shown in Fig. 1. This configuration marks a veritable landmark in the evolutionary path of a nebula. Until this configuration is reached the effect of shrinkage can be adjusted, and is adjusted, by a mere change of shape ; the mass carries the same angular momentum as before, in spite of its reduced size, by the simple expedient of rotating more rapidly, and restores equilibrium by bulging out its equator. But mathematical analysis shows that this is no longer possible when once this landmark has been passed. Further shrinkage now involves an actual break-up of the nebula, the excess of the angular momentum beyond that which can be carried by the shrunken mass being thrown off into space by the ejection of matter from the equator of the nebula.

We have so far spoken of the nebular equator as being of circular shape, as it undoubtedly would be if the nebula were alone by itself in space. But an actual nebula must have neighbours, and these neighbours will raise tides on its surface, just as the sun and moon raise tides on the surface of the rotating earth. Whatever the neighbours are, there will always be two points of high tide antipodally opposite to one another, and two points of low tide intermediate between the two points of high tide. Thus the equator, instead of being strictly circular, will be slightly elliptical.

If the equator of the nebula had been a perfect circle, and if the nebula had been in all respects symmetrical about its axis of rotation, the ejection of matter would have started from all points of the equator simultaneously. Indeed, there could be no conceivable reason why it should start at one point rather than at any other point. But in Nature we do not expect to find perfect balances of this kind ; if the main factors are of exactly equal weight some quite minor factor invariably intervenes to turn the balance in one direction or another. In the present problem
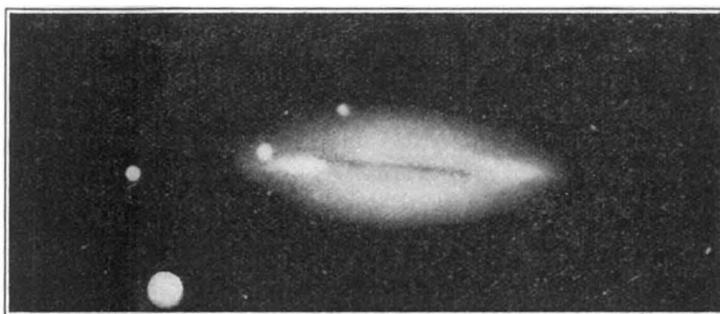

FIG. 2.—Regular shaped nebula (N.G.C. 5866) with band of dark matter on equator.

there could be no choice as between one point of the equator and another if the various minor factors were absent, but when these minor factors come into play, a discrimination at once takes place. Assuming, as seems likely, that the tidal irregularities are the minor factors which determine the choice of points for the ejection of matter, mathematical investigation shows that the ejection of matter will take place from the two antipodal points on the equator at which the tide is highest. The equator being slightly elliptical, these points are of course the ends of its major-axis. After the nebula has passed its critical landmark, shown in Fig. 1, its shape ought to be similar to the lenticular figure which formed the landmark, but with the additional feature of matter streaming out from two antipodal points on its equator.

This describes exactly what is observed in the spiral nebulæ. Fig. 2 (N.G.C. 5866) shows a nebula in which the ejection of matter is just beginning ; we notice the bulge along the equator and the dark band which we may assume represents ejected matter which is already cooling. Fig. 3 (N.G.C. 4594) exhibits a more

advanced state of development; and Fig. 4 (N.G.C. 891), a still later one in which the ejected matter already dwarfs the central nucleus in size, although probably not in total mass.

In all these figures we are looking at the nebulæ very approximately edge-on. Fig. 5 (M. 51) shows the well-known "whirlpool" in Canes Venatici, a nebula which may be very similar physically to that shown in Fig. 4, but we see it face on: we are

FIG. 3.—Regular shaped nebula (N.G.C. 4594) with ring of dark matter surrounding equator.

looking along its axis of rotation. Again the central nucleus occupies only a small part of the picture. Figs. 6 (M. 101) and 7 (M. 81) show two nebulæ, the evolution of which has proceeded still further, so much so that in the last of these there is very little nucleus left, and by far the greater part of what we see is what we believe to be ejected matter.

In both of these last two nebulæ it will be seen that the arms of ejected matter proceed from two antipodal points, exactly as required by dynamical theory. So far we have spoken of the matter in these arms as ejected matter because theory has suggested this interpretation, but we need not be satisfied with theory ; there is very direct observational evidence on the point. Various astronomers, especially Van Maanen, have detected motion in the arms of many nebulæ, including the three shown in Figs. 5, 6, and 7. Their observations show that the arms are in real truth jets of matter coming out of the nucleus. Fig. 8 shows the motion found by Van Maanen for about 100 points in the nebula M. 81, the arrows showing the motion in a period of 1300 years,[2] and the measures on the various other nebulæ show substantially similar results ; you will see that there is little room for doubting that the arms consist of matter flowing out of the nucleus. On measuring the actual velocities of flow it is found that in nebula M. 51 (Fig. 5) a particle of the jet makes a complete revolution around the nucleus in about 45,000 years ; in M. 81 (Fig. 7) the corresponding figure is about 58,000 years, and in M. 101 (Fig. 6) about 85,000 years. From these figures it is possible to estimate the density of the

[2] The points surrounded by small circles are stars which are believed to have no physical connexion with the nebula.

matter in the nucleus. It is found that the densities must be of the order of 10^{-16} gm. per cubic centimetre, a figure representing a vacuum more perfect than any obtainable in the laboratory. The small amount of gas in an ordinary electric light bulb, if spread out through St. Paul's Cathedral, would still be something like 10,000 times as dense as the nucleus of a spiral nebula.

The nebula shown in Fig. 4 exhibits a lumpy or granulated appearance in its arms. In M. 51 (Fig. 5) this takes the form of pronounced condensations, and in the outer regions of M. 101 (Fig. 6) and M. 81 (Fig. 7) these condensations have further developed into detached and almost star-like points of light.

When gas is set free out of an ordinary nozzle into a vacuum it immediately spreads into the whole of the space accessible to it. Why then does not the jet of gas shot off from the equator of the nebula do the same ? The explanation is to be found in the gigantic scale on which this latter process takes place. As we increase the scale of the phenomenon the mutual gravitational attraction of the particles of gas becomes
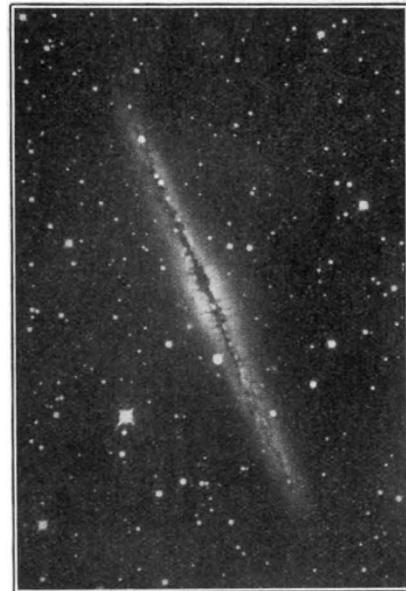

FIG. 4.—Spiral nebula (N.G.C. 891) seen edge on.

of ever greater importance until finally, by the time nebular dimensions are reached, gravitation overcomes the expansive influence of gas pressure and is able to hold the jet together as a compact stream. But, as soon as this happens, dynamical theory predicts that a further phenomenon ought to appear. As regards the distribution of density along the filament, the influence of gas-pressure is in the direction of

process we have been considering—we have been watching the creation of the stars. In Fig. 1 we saw the raw material—a gaseous mass of extreme tenuity, already moulded, as a result of shrinkage and consequent increase of rotation, to the stage at which disintegration is about to commence. Further shrinkage takes place, and in Figs. 2 and 3 we see the ejection of jets of gas from which the future stars will in due course be made. In Figs. 4 and 5 individual stars are beginning to form, although at present only as vague condensations in what is still a continuous nebular mass. Finally, the outermost parts of Figs. 6 and 7 show us the finished product—separate masses, although still far more tenuous than ordinary stars, starting off on their independent existences. Each of these masses will go through the changes we have already briefly described. It will contract, getting hotter in doing so, until it reaches a maximum temperature just as the gas-laws are beginning to fail, after which it cools and contracts into a dead dark mass.

The family of stars born out of a single nebula may be millions in number. They may either mingle with the general mass of the stars or, if the original nebula was sufficiently remote from the main universe of stars, may form a separate colony by themselves. In illustration of the former

FIG. 5.—Spiral nebula in Canes Venatici (M. 51).

keeping the density spread out uniformly, while that of gravitation is towards making the stream condense with compact globules. When nebular dimensions are reached the latter tendency prevails, and the issuing jet of gas breaks up into drops much as a jet of water issuing from a nozzle does, although for a very different physical reason. In the photographs reproduced in Figs. 4, 5, 6, and 7 we can trace this process going on.

Dynamical theory not only predicts that these globules of gas must form, but also enables us to calculate their size, mass, and distance apart. A comparison between their distance apart, as calculated in kilometres, and their angular distance apart, as observed in the sky, leads at once to an estimate of the distance of the nebula to which they belong. It is gratifying to find that estimates of nebular distances made in this way are in good agreement with estimates made in other ways. The calculation of the masses of these condensations leads to a still more interesting and significant result. In every nebula for which the calculation can be made, the calculated mass of a single condensation proves to be approximately equal to the mass of the average star.

This gives, I believe, the key to the evolutionary

FIG. 6.—Spiral nebula in Ursa Major (M. 101).

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alternative, numbers of groups of stars are known—*e.g.* the Pleiades, the stars of the Great Bear—in which all the members have a common velocity and, generally speaking, similar physical constitutions also. All the stars of any such group are voyaging through space together, and have obviously done so since they first came into being. The alternative possibility of a family of stars forming a detached colony by themselves is perhaps exemplified in the so-called "globular" star-clusters, such as the well-known cluster in Hercules (Fig. 9). These are globular only in name, for Shapley has found that

hood of the sun formed what he described as two "star-streams," each stream moving with its own velocity in space. Except that it begs the question as to the extent of these streams in space, it would have been equally accurate to describe them as forming two intermingled moving clusters. Shortly after, Eddington and Halm, independently, found a third stream or moving cluster, constituted of the very hot stars which the astronomer classifies as stars of types B and O. In this case we know the extent of the cluster in space and also its approximate shape. According to Charlier, it is shaped like a round biscuit
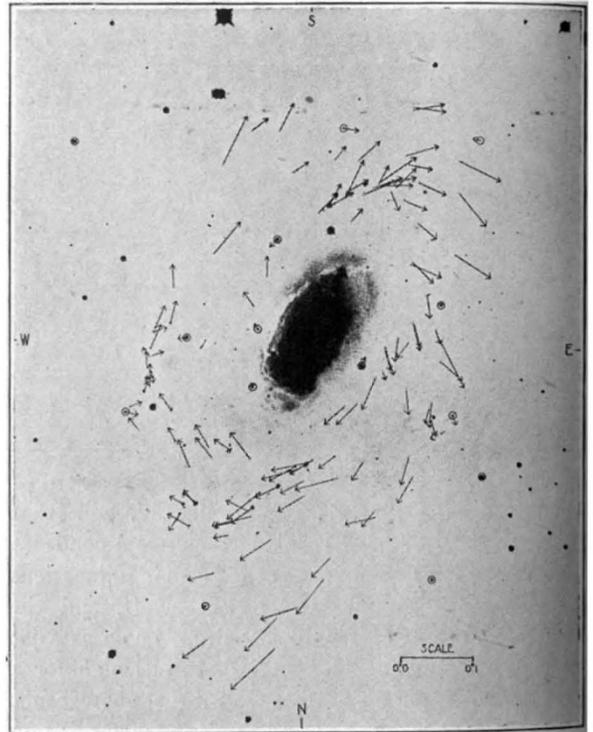

FIG. 7.—Spiral nebula in Ursa Major (M. 81).

FIG. 8.—Motion in the arms of the spiral nebula M. 81.

they are of an elliptical structure, showing symmetry about a plane precisely as might be expected if they were the final product of a rotating nebula.

Probably we ought not to regard the two possibilities just mentioned as sharply cut alternatives. It is more likely that they represent the two extreme ends of a continuous chain of possible histories for the family of stars born out of a single nebula. It seems quite possible that what we describe as " the main mass of the stars " may be nothing more than a collection of clusters of stars, each cluster having originated out of a single nebula. The clusters are by now so intermingled that it is difficult to look on them as distinct groups of stars, although we can still find some evidence that this may be the proper way of regarding them. In 1905 Kapteyn showed that the stars in the neighbour-

lying parallel to the Milky Way, its diameter being about 2·8 times its thickness. Any cluster of stars having a common origin, whatever shape it may assume at first, will be rapidly knocked out of shape when it begins to intermingle with other stars. Dynamical theory shows that after it has been knocked about *ad infinitum* in our universe of stars, such a cluster ought to assume the shape of a round biscuit parallel to the Milky Way, the ratio of its diameter to its thickness being about 2·5. This agrees sufficiently well with what is observed to suggest that all the stars in this stream have a common origin, and the same is true of many of the smaller known moving clusters, such as the Ursa Major cluster already mentioned. Thus, although we cannot claim that anything is definitely proved, there is every justification for thinking of the main mass of the stars

as a jumble of intermingled moving clusters, each cluster owing its existence to a separate nebula. This possibility has no very direct bearing on the question of the origin of our solar system ; it has been mentioned merely as rounding off our knowledge of what appears to be the main evolutionary process of the stars.

In all its essentials except one, this evolutionary process is similar to, and in its earlier stages almost identical with, that which Laplace, in his famous nebular hypothesis, imagined as the origin of the solar system. We have seen before our eyes the rotating and shrinking nebula finally shedding matter from its equator ; we have watched the condensation of this matter into separate masses, and have finally witnessed the start of these detached masses on their voyages into space, all precisely as pictured by Laplace.

The one essential difference is that of size. The evolutionary process we have been watching occurs on a scale such as Laplace never dreamed of. His primeval nebula was supposed to be of about the size of Neptune's orbit, a size represented on the scale I used at the beginning of this lecture by a threepenny-bit. On this same scale the nucleus alone of a good-sized spiral nebula, such as those shown in Figs. 6 and 7, would be about the size of the Albert Hall, while the arms would sprawl over the whole of Hyde Park and Kensington. The pictures of these nebulæ that you have before you would have to be enlarged to the size of a whole country, or even possibly of a whole continent, before a body the size of our earth became visible in them at all.

Although the parent nebulæ we have been considering are all incomparably greater than Laplace's imaginary nebula, yet each tiny condensation, as it starts off into space, is a gaseous nebula the mass of which is just about equal to that imagined by Laplace and the size of which is not perhaps very greatly different. If, then, this younger generation of nebulæ meet with the same experiences in life as their giant parents before them, we should not have to look far for an explanation of the origin of the planets, and if the third generation again repeated the experience of their ancestors, the satellites of the planets are also accounted for. But mathematical research and observation agree in disposing of so simple an explanation of the origin of the solar system.

As we have seen, it is only because the filaments in the spiral nebulæ are of such huge size that gravitation is able to cause condensation in opposition to the expansive tendency of gas-pressure. A nebula of mass comparable to our sun might go through the same life-history as the bigger nebula until matter began to be thrown off from its equator, but after this the difference of scale would begin to tell, and the subsequent course of events would be widely different. The ejected
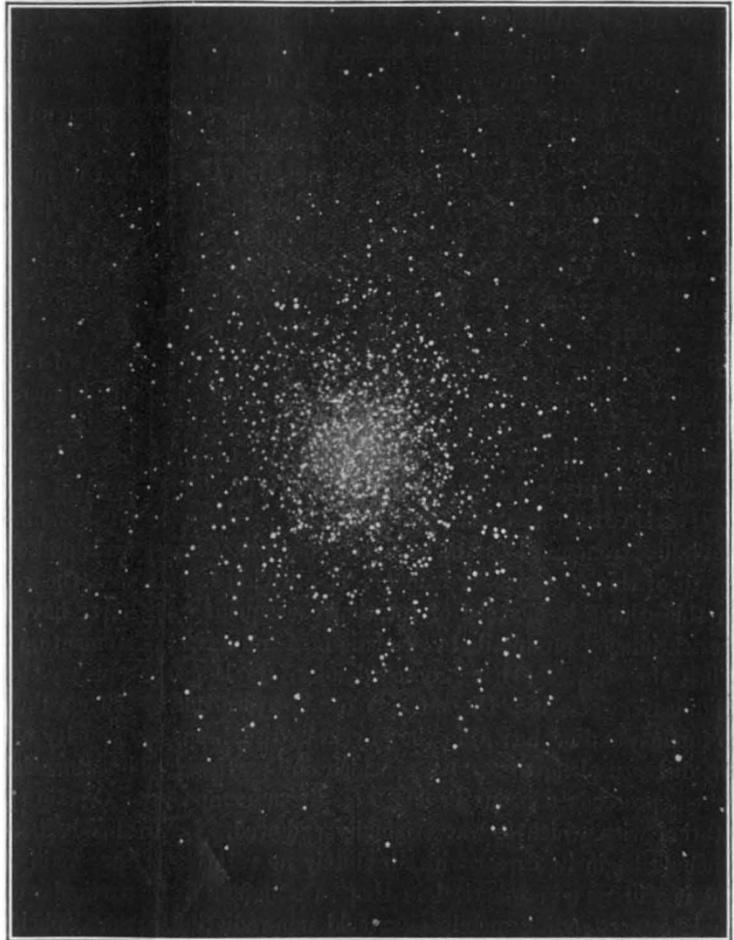

Fig. 9.—Star-cluster (M. 13) in Hercules.

matter could not condense into filaments, still less into detached globules ; it would merely constitute a diffuse atmosphere surrounding the parent nebula. As such a system shrunk by the emission of radiation, the constancy of angular momentum would, at first, merely demand that more and more gas should be transferred from the centre to the atmosphere.

But mathematical investigation shows that in time, after the central star had shrunk to a certain critical density, perhaps somewhere about one-tenth of that of water, a cataclysmic period would ensue, from which the mass would emerge as a binary star—two stars of

comparable masses revolving about one another nearly in contact and in approximately circular orbits. This is a formation with which the practical astronomer is very familiar. He finds that a very large proportion— perhaps about one-half—of the stars in the sky are binary, and he can detect an evolutionary sequence in these binary stars. The sequence starts with the formation just described in which the two constituent stars are almost in contact. As it progresses the stars move ever farther and farther apart, while the eccentricity of their orbits increases. Theory indicates that the process of fission which has broken up the original star into two constituents may repeat itself in either or both of these constituents, so that the final product may be a " multiple " star of either three or four constituents. Prof. H. N. Russell, investigating this question theoretically, found that certain numerical relations must hold between the relative distances of the various constituents of a multiple star : he also showed that the predictions of theory are confirmed quantitatively by observation.

So far, then, theory and observation have gone hand-in-hand. We have traced the evolution of astronomical matter through stages of ever-increasing density, from the most tenuous of nebulæ to the densest of multiple stars, and at almost every stage observation has confirmed the predictions of theory. Not all astronomical matter will traverse the whole length of this evolutionary course. The driving force on this course is increase of rotation consequent on the shrinkage produced by emission of radiation. When the shrinkage has proceeded a certain length solidification sets in ; the rotation can increase now no further, and evolution, in the physical sense, stops. The distance along the course to which any particular system proceeds depends in effect on the amount of rotation with which it was originally endowed. Let a nebula begin its career with absolutely no rotation, and it will remain spherical in shape throughout its whole career, ending merely as a cold non-radiating, but always spherical, mass. Such a nebula never even gets away from the starting-post. It is true that this is not a likely event, but for aught we know many a nebula may freeze and die before reaching the critical configuration (Fig. 1) at which the birth of stars first commences. Similarly many of the stars may become cold and so cease to develop without ever attaining the stage at which binary systems are formed. In the same way many binary systems must fail to develop into multiple systems. Here again observation is with us : there are ten times as many purely binary systems known as there are multiple systems which have proceeded beyond the binary stage. Theory has traced out for us the whole length of the evolu-

tionary course, but theory and observation agree that not many systems stay out the whole course.

We now come to the crux of the whole question. Nowhere on this course have we found our solar system, or anything in the least degree resembling it. If our sun had been unattended by planets we should have had no difficulty in guessing its origin. It might reasonably be supposed to have been born out of a nebula in the normal way, but to have emerged with insufficient rotation to have carried it on to the later stages of fission into a binary or a multiple system. It might, in fact, be supposed to have had the same evolutionary career as half of the stars in the sky. In support of the conjecture that our sun had been born out of a nebula in the ordinary way, we could note that its mass is about equal to what we calculate ought to be the mass of a star born out of a nebula, and that it is, apart from its planets, similar in every way to millions of other stars to which we may ascribe a nebular origin. In support of the conjecture that it had stopped short on its evolutionary course from want of adequate rotation to carry it on further, we should merely have to note the slowness of its present rotation. A simple calculation shows that the sun has only a small fraction of the amount of angular momentum requisite for fission. Even if we add the angular momentum of all the planets, as we ought if we suppose that these at one time formed part of the sun, the result is the same—the whole system can never have had more than a fraction of the angular momentum necessary for a rotational break-up into a binary star.

Thus the sun is a quite intelligible structure. The difficulty of our problem is not the origin of the sun, but the origin of the planets and of their satellites.

Certain special types of astronomical structure have already been mentioned as not falling into place on the main line of evolutionary development. The particular examples chosen were the planetary nebulæ, the Cepheid variables, and the long-period variables. The question now arises as to whether we must add the solar system to the list. The circumstance that certain structures do not find a place in the evolutionary main line suggests that off this main line may be branch lines on to which the development of a system may in certain circumstances be turned. This indeed is only what might be anticipated. We should no more expect two stars to have precisely the same experiences in their careers than we should expect it of two humans. Our normal star has been supposed to develop in a universe of its own, where its angular momentum remained constant and where it was in every way unmolested by its neighbours. The mathematician finds it convenient to allot a whole

infinite universe to each star, but Nature does not. Nevertheless, the conditions postulated by the mathematician are nearer to the truth than is often the case in his idealised problems. On the scale we have already used, on which the sun was represented by a microscopic particle $\frac{1}{10000}$ inch in diameter, the most gigantic of known giant stars may be represented by a pin-head one-thirtieth of an inch in diameter. The present spacing of the stars is such that on this scale there is less than one star to a volume equal to the interior of St. Paul's Cathedral. Space then cannot be said to be overcrowded, and although it is possible that the stars may disturb one another as they move in their courses, it is clear that any serious disturbance of one star by another must be a rather exceptional event. Obviously we have been right in regarding the evolution of a star entirely undisturbed by its neighbours as the normal course of evolution, and we can now see why the vast majority of stars follow this normal course.

To all appearances, the stars which have been sidetracked off this normal course are extraordinarily few in number. The total number of stars in the sky is about equal to the total population of the earth ; the number of known exceptional systems would at most populate one small town, although, of course, we can scarcely even conjecture how many exceptional systems there may be which are still unknown to us. There is no reason for supposing that the side-tracking influence has in every case been a neighbouring star, but the systems known to be exceptional are sufficiently few to suggest that this may have been the cause in a large proportion of cases.

The immediate question before us, however, is not that of the exceptional systems in general, but of our own solar system. Was it a neighbouring star that threw it off the main line of evolutionary development ? Here, for the first time, observational astronomy denies us any help. Not a single system is known outside our solar system which resembles it in the least degree. The reason is not that no such system exists, but that we could not see it if it did. An astronomer on a distant star observing our system would see Jupiter as the brightest object after our sun, but the ratio of their luminosities would be as three hundred million to one. Seen from our nearest known neighbour in space, Proxima Centauri, the sun would appear as a first magnitude star, and Jupiter as a star of magnitude 22·2, the distance between them being at most four seconds of arc. A star of magnitude 22·2 is still well beyond the range of our largest telescopes, and would be doubly invisible if it had a first magnitude star only four seconds away. We must wait for a very great increase in the power of our telescopes before there will be any hope of seeing systems similar to our own in the sky, even if they exist no further away from us than Proxima Centauri. Thus it is clear that our discussion has now left the regions in which observation can be called upon to make suggestions or to check our conclusions : henceforth we have theory alone to guide us.

Let us start on our quest by noticing that our solar system has quite clearly marked characteristics. It is no mere jumble of bodies looking as though they had fallen together by accident—had it presented this appearance the problem of its origin might reasonably be dismissed as hopeless. Not only has the principal system of the sun and its planets got clearly marked characteristics, but also these same characteristics reappear in the smaller systems formed by Jupiter and Saturn, each with its family of satellites. Each of these small systems is, to all intents and purposes, a replica in miniature of the solar system, so much so that no suggested origin for one system can be regarded as satisfactory unless at the same time it explains the origin of the other two. The principal features common to the three systems are, that the orbits in all three systems are, with few exceptions, all in or close to one plane, that these orbits are all described in the same direction, and that the masses of the secondaries, whether planets or satellites, are all small in comparison with those of the primaries around which they revolve. Thus the sun has a mass equal to 1047 times that of his greatest planet Jupiter; while Jupiter's mass is about 11,000 times that of his most massive satellite. The smallest disparity in mass is found in our own Earth-Moon system with a mass ratio of 81 to 1. In systems possessing many satellites (those of the sun, Jupiter, and Saturn) there is a general tendency for the masses to increase up to a maximum as we pass outwards through the system, and then to decrease to a minimum. Thus in the main system there is a regular progression through Mercury, Venus, Earth, Mars to the maximum mass of Jupiter, broken only by the anomalous position of Mars, while on the descending side the progression through Jupiter, Saturn, Uranus, Neptune fails in regularity only through Neptune being some few per cent. more massive than Uranus.

The main line of evolutionary progress has been supposed to be that of a mass of shrinking, rotating matter—first gaseous, then liquid, then solid—left to itself in space. Such a system must show one very marked characteristic throughout its whole career, namely, a plane of symmetry. In its earliest stage of all, when the system is a mere chaos of independent molecules, the plane will coincide with what mathematicians describe as the " invariable plane " of the

system. Later, when the mass has assumed the regular shape of a rotating nebula, the plane is the equatorial plane of the nebula, the plane in which the arms subsequently appear and in which the stellar condensations start off in their orbits. The symmetry of spiral nebulæ about their equatorial planes would of itself suggest strongly that they have developed to their present formations as rotating bodies practically undisturbed by external influences.

If our solar system had developed out of an undisturbed rotating mass, it too ought to exhibit a plane of symmetry. The orbits of nearly all the planets and their satellites do, in actual fact, lie very nearly in one plane, which, to this extent, is, of course, a plane of symmetry. But the sun's axis of rotation is not perpendicular to this plane; the sun has its own plane of symmetry in its equator, and this is inclined at an angle of $7°$ to the plane of orbits.

The existence of these two distinct planes is enough in itself to suggest that our system has not developed simply out of an undisturbed rotating mass. Thus, in tracing our system back to its origin, we naturally look at the effects to be expected from rotation plus some external influence. To a first rough approximation, it is natural to suppose that the plane of the sun's equator records the plane of rotation of the original system, while the plane of the planetary orbits was in some way determined by the extraneous disturbance.

Of all the interactions between two separate astronomical bodies, gravitational attraction is likely to be by far the most potent. The moon has been accused of exerting all kinds of influences on our earth, as, for example, on its weather, on the destinies, the emotions, and even on the sanity of its inhabitants; but the only influence which survives scientific examination is gravitational attraction as evidenced by the semidiurnal tides. It is true that a head-on collision between two astronomical bodies would produce more immediately dramatic results than a mere tidal pull; but we shall not consider such an event here. Head-on collisions must of necessity be exceedingly rare; systems that experience them would undoubtedly be deflected from the main line of evolutionary progress on to a branch line; but it does not seem likely that this branch line contains systems like our own. As time does not permit the exploration of all conceivable branch lines, let us turn at once to that which seems most likely to reveal the origin of our system—the branch line that diverges from the main line at the occurrence of a violent tidal encounter.

On the earth, our moon raises tides the average height of which at high tide is only a few feet. This height of high tide is only about a ten-millionth part of the earth's radius, a fraction which we may designate as the tidal fraction. If the moon were ten times as massive, the tidal fraction would be increased ten-fold; if it were brought to half its present distance, the tidal fraction would be increased eight-fold. If we agree to measure masses in terms of the body on which the tide is raised as unity and to measure lengths in terms of the radius of the same body, then the tidal fraction is equal to the mass of the tide-generating body divided by the cube of its distance, say M/R^3. Using this formula, we find that our nearest neighbour Proxima Centauri raises on the sun a tide of quite infinitesimal magnitude; the tidal fraction is about 10^{-26}, and the actual height of tide is of the order of 10^{-15} cm. or, say, one-fiftieth of the radius of an electron. This single illustration will show, and with some margin to spare, that under normal conditions the tidal influence between neighbouring stars is utterly insignificant. For tidal forces to become important to cosmogony, conditions must be abnormal.

Our sun happens at the present moment to have no especially near neighbour; but it is fairly certain that at some time, in its wanderings through the stars, it must have passed stars within a much less distance than that which now separates it from Proxima Centauri. The most trustworthy lines of evidence as to the earth's age, namely, those from geology and radioactivity, indicate an age of from 800 to 1100 million years. For precision, let us think of the sun's age as 1000 million years. Let us imagine for the moment, what is no doubt very far from the truth, that throughout all this thousand million years the sun and all the stars have moved just as they are moving now, with the same average velocities as now and keeping at the same *average* distance apart. Throughout this thousand million years the distance of our sun from its nearest neighbour will have been continually changing, and one star after another will, of course, have taken up the rôle of nearest neighbour. But there must have been some one instant in this thousand million years at which our sun was nearer than at any other instant to its nearest neighbour. A calculation based on the theory of probability indicates that this nearest distance is likely to have been of the order of 7×10^{15} cm., a distance which, although only a six-hundredth of that which now separates us from Proxima Centauri, is still equal to fifteen times the radius of Neptune's orbit. Even if the sun had filled the whole of Neptune's orbit, the tidal fraction at this closest encounter, on the supposition that the nearest star had a mass equal to the sun, would only be equal to $1/(15)^3$ or $1/3375$, giving a height of tide which is quite unimportant from the point of view of cosmogony. So long as things have been as they now are, tidal actions between separate stars must have been quite devoid of cosmogonic interest, except possibly in very special cases of quite exceptionally close approaches.

It is, of course, possible that our sun was the victim of one of those exceptionally close encounters. Nothing can be brought against the supposition of such an event, except its *a priori* improbability. The result of such a close encounter might, as we shall see, be the creation of a system in many ways resembling our solar system.

Our calculations of probabilities and improbabilities have, however, rested upon the admittedly erroneous assumption that stellar conditions have been similar to the present ones for a period of a thousand million years. On looking back through the past history of the universe, we come to a time when conditions must have been very different from what they are now. We come to a time, which we have already considered, when our sun had not yet assumed its present stellar characteristics. It was a condensation in the arm of a spiral nebula moving with thousands of similar condensations towards a free career in space. Its density was enormously lower than it now is, and its size correspondingly greater. It was also much

nearer to its neighbours than, in all probability, it has ever been since. In this early stage of its existence, the tidal effects of its neighbours may well have been enormous ; we shall pass to exact figures in a moment.

In general, the passage of one star past another merely raises a tide which subsides as the tide-raising body recedes. Even when the approach is so close that the height of the tide raised is greater than the original radius of the star, the recession of the disturbing star may result in the disturbed star relapsing merely to its original spherical form. But there is a limit which must not be passed, and if the disturbing body passes this limit, all hope of the star resuming its original shape is lost. The distance of the limit depends primarily on the mass of the disturber ; to a lesser degree it depends on the rotation, shape, and density-distribution of the primary star ; and to some extent it depends on the velocity of the two stars relative to one another. We shall get a tolerable idea of the march of events if we suppose the primary star to be surrounded by an imaginary sphere the radius of which depends solely on the mass of the disturbing star. If this mass is equal to the mass of the primary, the radius of this imaginary sphere will be about $2\frac{1}{4}$ times the radius of the primary ; if the disturbing star has eight times the mass of the primary, the radius of the imaginary sphere will be $4\frac{1}{2}$ times that of the primary, and so on. So long as the centre of the visiting star remains outside the sphere, a tide is raised which recedes as the visiting star disappears, but the moment the visiting star invades this sphere, an entirely new phenomenon appears.

As the approach of the disturber raises the tide to higher and higher levels, the highest points of the tide move ever farther away from the star's centre, into regions where the gravitational attraction of the star gets weaker and weaker. At the same time, of course, the gravitational pull of the visiting star gets stronger and stronger. Finally, just as the visiting star crosses the critical sphere, its gravitational pull just balances that of the primary—it is this condition that defines the critical sphere. If the visiting star further invades this critical sphere, the particles at high tide are shot away from the primary star, the resultant gravitational force on them now being definitely towards the visiting star ; they are of course immediately replaced by others which are shot off in turn, and so on. The total effect is that a filament or jet of gas is shot out from the point of high tide. Each particle of this jet moves under the combined forces of the primary and of the visiting star, and the problem of determining its orbit is a special case of the problem of three bodies, which unfortunately is not soluble. But the general result is that the jet undergoes various contortions while moving all the time in the plane which contains the orbit of the visiting star.

If such a jet had been thrown off the sun simply by an increase of rotation consequent on shrinkage, its gravitational attraction would, as we have seen, be inadequate to resist the expansive effect of its own gas-pressure, and it would have been rapidly dissipated away into space. In the present situation conditions are very different, the essential difference being that, while shrinkage from loss of radiation is a very slow process,

tidal disruption may be a very rapid process. The rate of a star's rotation will alter but slightly in a thousand years, whereas ten years may suffice for a tide-raising body to come, do its work, and go away again. The filament of gas set free by increase of rotation would be of extreme tenuity ; a filament set free by a tidal cataclysm might easily be of sufficient substance for its own gravitation to hold it together as a compact whole.

If gravitation is potent enough to do this, it will also be potent enough to break up the filament into condensations, just as the filaments of spiral nebulæ are broken up into condensations. But here again an essential difference must be taken into account. The shrinkage of a spiral nebula is a slow secular process. Year after year, and century after century, the filament will be ejected without change of character—the process may be compared to the paying out of a coil of rope. But the tidal disruption of a star is a rapid, even cataclysmic event : within a few years the emission of the filament starts, reaches a maximum, declines, and ends. There is no steady paying out here ; the process ought rather to be compared to the discharge of a torpedo, or other body which is thickest in the middle and tapers off at the two ends. When a filament of this shape breaks up into condensations it will form no long chain of similar masses, but a small number of unequal masses. It is natural to conjecture *a priori* that large masses are likely to form out of the central portions where matter is most plentiful, and smaller masses at the ends where matter is scarce. Such a question cannot of course be finally settled by *a priori* conjectures, but in the present case an exact discussion of the problem indicates that the *a priori* view is the right one, and suggests that the comparative abundance of matter in the central part of the filament may provide an explanation of the appearance of the more massive planets, Jupiter and Saturn, near the centre of the sequence of planets.

Obviously, if a tidal cataclysm can explain the existence of the planets, it can also, in general terms at least, explain the existence of the satellites of these planets. For immediately after the birth of any planet, say Jupiter, the original situation repeats itself in miniature. Jupiter now plays the part originally assigned to the sun, while either the wandering star or the sun itself, or possibly the combination of the two, acts the part of the tide-raising disturber. Again we get the emitted filament, again the formation of condensations, and again, as the ultimate result, a sequence of detached bodies with the most massive in the middle. Since Jupiter, the sun, and the disturbing star all move in the same plane, namely the plane of Jupiter's orbit, it follows that Jupiter's satellites, when formed, ought also to move in this plane, as in actual fact they are observed to do.

So long as we merely discuss the matter in general terms it looks as though the process might go on for generation after generation, each member of a family of satellites producing minor satellites to circle round itself, and so on *ad infinitum*. Common sense suggests that this cannot go on for ever : there must be a limit somewhere. Exact calculation confirms the view of common sense, with the disconcerting addition, that we are in danger of overstepping the limit if we attempt

to account for the whole of the satellites in the solar system in the way just suggested.

I have already mentioned a mathematical formula which enables us to calculate the masses of the bodies formed out of the condensations in the arms of spiral nebulæ. The same formula puts us in a position to calculate the masses of the planets which ought to be formed from the filament drawn out of the sun. Let us suppose that when the tidal cataclysm took place the sun had a radius equal to that of Neptune's orbit, and therefore a mean density of 5.5×10^{-12}. Let us suppose that at the middle parts of the ejected filament the mean density was one-tenth of this, or 5.5×10^{-13}. Let us further suppose that the temperature of the ejected matter corresponded to a molecular velocity 4×10^4, this being about the molecular velocity of hydrogen or oxygen at their ordinary boiling-points. Then our formula indicates that the masses of the planets formed out of the middle parts of the filament ought to be about 10^{30} gm., a mass intermediate between those of Jupiter and Saturn. This is satisfactory as showing that there is no numerical difficulty in supposing Jupiter and Saturn to have come into being in the way we have imagined. If we like to accept the tidal theory of their birth, we can reverse our calculation and can calculate from their present known masses what must have been the density of the matter from which they were formed.

Naturally an inverted calculation of this kind is not applicable only to Jupiter and Saturn ; if the tidal hypothesis is correct, it must be applicable to all the planets and to all their satellites. For example, the first five satellites of Saturn all have masses of about 5×10^{23} gm. ; our calculation shows that if these satellites came into being as gaseous condensations in a filament, the gas in this filament must have been anything from one to a million times as dense as lead. Such a conclusion is, of course, preposterous : the only proper conclusion is that these satellites cannot have originated as gaseous condensations.

This conclusion is not surprising, or even unexpected. Even now these satellites, on account of the smallness of their mass, are incapable of retaining a gaseous atmosphere, whence it follows that they can never have existed in the gaseous state. They must have been born either liquid or solid.

In this way we come upon the practical limitation to the possibility of endless generations of satellites being born. Primarily it is that after a time the satellites would be too small for their gravitation to hold them together. A brief reprieve from the operation of this law is afforded by the possibility of the matter liquefying or even solidifying before it scatters into space, and it is probably owing to the operation of this reprieve that all the satellites of the planets, and probably also the smaller planets themselves, owe their existence.

What of our Earth, which interests us above all other planets ? Its present mass is rather too small to have been born out of a purely gaseous filament, but we must remember that if it were born gaseous, a large part of its mass might be immediately dissipated away into space, the present Earth representing only a remnant of a once much more massive planet. This line of investigation leads nowhere. A more promising line of attack is through a consideration of our satellite the moon. The more liquid a planet was at its birth the less likely was it to be broken up tidally by the still gaseous sun, but, in the event of this breaking up taking place, the ratio of mass between satellite and primary would be much nearer to unity than in the case of a wholly gaseous planet. Thus, as we pass from planets which were wholly gaseous at birth to planets which were wholly liquid, we ought to start from planets with large numbers of relatively small satellites and, after passing through the boundary cases of planets with a small number of relatively large satellites, reach planets having no satellites at all. This is precisely what we find in the solar system. Leaving Jupiter and Saturn each with their nine relatively small satellites we pass through Mars with its two satellites to the Earth with one relatively very large satellite, and after this come to Venus and Mercury with no satellites at all. Proceeding in the other direction from Jupiter and Saturn, we pass through Uranus with four small satellites to Neptune with one comparatively big satellite. Looked at from this point of view, the Earth-Moon system figures as the obvious boundary case between the planets which were originally liquid and those which were originally gaseous, the corresponding boundary case on the other half of the chain being Neptune. Thus we can conjecture that Mercury and Venus were born liquid or solid, that the Earth and Neptune were born partly liquid and partly gaseous, and that Mars, Jupiter, Saturn, and Uranus were born gaseous.

We have already noticed that Mars and Uranus both have masses which are too small for their positions in the sequence of planets. If the planets were born out of a filament of continuously varying density, the mass of Mars at birth ought to have been intermediate between that of the Earth and that of Jupiter, and similarly the mass of Uranus at birth ought to have been intermediate between that of Neptune and that of Saturn. We have, however, just seen reasons for conjecturing that the two anomalous planets, Mars and Uranus, were the two smallest planets to be born in the gaseous state ; they would therefore be likely to lose more mass by dissipation of their outer layers than any of the other planets. Let us introduce the supposition that Mars, and to a lesser degree Uranus, lost large parts of their mass by dissipation into space ; let us suppose that they are mere fragments of what were originally much more massive planets, then all anomalies disappear, and the pieces of the puzzle begin to fit together in a very gratifying manner.

Nevertheless, and in spite of the high promise which the tidal theory seems to hold out, it is far too early to claim that it can finally explain the origin of our system ; its claim to consideration at present is rather that, so far as I know, it provides the only theory of that origin which is not open to obvious and insuperable objections.