The Origin of the Solar System.*

By SIR JAMES JEANS, F.R.S.

THE observational astronomer generally feels only an indirect interest in the problem of how our earth and its companion planets came into being; his telescope can give him no direct information on the subject, since such planets as other suns may possess are too small and too distant to be observed. If every star in the sky were suddenly to give birth to planets we should in all probability remain unaware that anything was happening.

Yet the problem is of thrilling interest to science in its widest sense. The old nebular hypothesis of Laplace had pictured the stars as shrinking nebulæ which rotated faster and faster as they shrank, and in so doing threw off their equators rings of matter, each of which was destined in time to condense into a planet. This cosmogony implied that the shedding of planets was a normal event in the life of a star. It led to the concept, so commonly held in the nineteenth century, that every star in the sky was a sun distributing light and heat to a retinue of worlds circling round it. As solar light and heat are the most obvious essentials for terrestrial life, it was natural to take the next step and assume that every star we saw in our telescopes was busily at work radiating energy to maintain life on its surrounding planets. When once this step had been taken, no great violence to the probabilities seemed to be implied in taking the further step of assuming that each star had been created to this special end.

The more modern view supposes that the birth of planets is very far from being a normal event in the life of a star—it is an abnormal and exceedingly rare event. So rare is it that, even if the stars have already lived the longest lives that have ever been suggested for them—lives reaching back many millions of millions of years into the past—only a minute fraction of them can be surrounded by planets. If they are destined to live into the future for the longest period that has ever been suggested—a period measured in hundreds of millions of millions of years—even by the end of this inconceivable length of time only a minute fraction of their total number will be surrounded by planets. This view implies that most stars must live and die without giving birth to planets at all—and even of those that do, the majority must be so cold and shrunken before their planets are born that there can be little or no question of their sustaining life.

In brief, the older theory, with the help of a little kindly imagination, depicted a universe teeming with life. The more modern theory depicts a universe which proceeds steadfastly on its way, while here and there, in insignificant corners and at infrequent intervals, a strange accident results in life stumbling into being. It can scarcely be a matter of indifference to science—and still less to humanity—which picture is correct.

Let us first consider some evidence of a purely physical nature. The activity of radium appears at first glance to be permanent; yet we know that it is no more permanent than anything else in Nature. All radium gradually loses its potency; it deteriorates, so that after about 1600 years it will be only half as potent as it is to-day.

The reason for this loss of potency is now well understood. It is that the radium gradually changes into something which is not radium, and has not the properties of radium—the debris of radium, let us call it. After 1600 years, a mass of pure radium becomes changed into half radium and half debris of radium. The potency is reduced to half because the amount of radium is reduced to half.

It follows that if we are given a mixture of radium and its debris, we can tell how long the radium has been at work to produce this debris. For example, if the amount of debris is equal to the amount of radium, we know that the disintegration of the radium has been in progress for 1600 years; if three-quarters of the mass is debris the process has been in action for 3200 years, and so on.

The time needed for a mass of a radioactive substance to change into half substance and half debris is known as the 'half-period' of the substance: it varies enormously for different substances. It is 1600 years for ordinary radium; for one radioactive substance, radium C′, it is only about a millionth of a second, while at the other end of the scale are substances for which the half-period is measured in thousands of millions of years. For thorium it is about 16,500 million years; for uranium, 4500 million years.

Now in various rocks in the earth's crust geologists come upon imprisoned uranium accompanied by debris of uranium. In no case is the mass of debris ever as great as the surviving mass of the uranium. There is only one possible inference—the uranium has not been imprisoned for as long as 4500 million years. The proportion of debris found in all samples of rock tells much the same story—the uranium has been imprisoned for a time of the order of 1500 million years. The rocks in which thorium is imprisoned have much the same thing to say—the thorium has been imprisoned for a time of the order of 1500 million years. We conclude that something like 1500 million years must have elapsed since the crust of the earth solidified. We can now add something for the time before solidification and we shall obtain the total age of the earth. From a study of the relative abundance of ordinary uranium and its isotope actino-uranium, Rutherford has been able to show that this total age cannot have been more than about 3400 million years.

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Shooting-stars or meteors confirm the story told by the earth's rocks. Occasionally one of these objects is too large to be completely vaporised by the resistance of the air, and what is left of it strikes the earth in the form of a large rock or stone known as a meteorite. Many of these bodies are found to contain imprisoned thorium or uranium, along with the debris of their disintegration. The amount of the latter makes it possible to estimate the length of time since the stone solidified. The time cannot be estimated with great accuracy, but no body that has been examined suggested a period of more than 2900 million years since solidification, and the majority appeared to be of about the same age as the earth. In a general way we may say that the length of time which has elapsed since the planets and other members of the solar system solidified cannot have been more than about 3000 million years.

This estimate depends solely on recent advances in physical science. The earlier cosmogonists had no means of forming such an estimate, and it would have been of little use to them if they had. It is important for us of to-day, because we can combine it with recent astronomical knowledge. We can tell how much the sun and stars have changed in 3000 million years. The sun is radiating its substance away at the rate of 360,000 million tons a day. This sounds like a very rapid rate of loss until we compare it with the huge total mass of the sun. We then find that radiation at this rate for 3000 million years scarcely affects the sun's mass at all. The mass of the sun, and indeed of all the stars, must have been very much the same 3000 million years ago as to-day. Furthermore, recent astronomical research has shown that the physical state of a star depends almost entirely on its mass—stars which have approximately the same mass as the sun are found to have also approximately the same physical constitution as the sun. Thus we must suppose that when the planets and meteors were born, the sun not only had the same mass, but also the same physical constitution and size as it has to-day.

This conclusion, based on evidence which can scarcely be challenged, provides a test which we may apply to the various theories of the origin of the solar system in turn. Let us first apply it to the most famous of all, the nebular hypothesis of Laplace. Laplace supposed that the sun started as a huge nebula, extending out as far as the orbit of the farthest known planet—to-day we must say as far as the orbit of Pluto; as it shrank with cooling it left behind it rings of matter which afterwards condensed and formed the separate planets. When the earth was shed, this nebulous sun would have a diameter equal to the present diameter of the earth's orbit. We see at once that this hypothesis cannot survive the test I have just described; and indeed there are many other tests, mainly of a dynamical kind, which it is equally unable to survive.

It would be an impossible task to test all the various theories of the earth's origin which might be propounded one by one. Let us notice that all such theories fall into two distinct classes, according as they suppose that the sun alone was concerned in the process of creating the planets, or that other bodies were concerned in addition to the sun.

If the sun alone was concerned it is difficult to discover by what mechanism the outermost planets could be projected to their present distances from the sun. We seem compelled to postulate some system of internal explosions as the origin of the planets, and this seems inconsistent with the present orderly arrangement of the planetary orbits. It also fails to explain why the systems of Jupiter and Saturn are so exactly like the main system of the sun in every respect except size. Indeed, this likeness is so marked that any theory which fails to explain it may safely be dismissed; we may be sure that the same mechanism must have produced these smaller systems as had already produced the main system. This test seems fatal to any hypothesis of explosions. It is straining probabilities far too much to imagine that a succession of explosions could produce anything so orderly as the main system of planets; it is straining them infinitely more to suppose that the same miracle could be repeated twice again to produce the similar systems of Jupiter and Saturn.

Thus there seems to be no alternative to supposing that at least one other body besides the sun was concerned in the birth of the planets. In 1750, Buffon imagined the planets to have been splashed out of the sun as the result of collision with a passing comet. In 1880, Bickerton propounded a somewhat similar theory, except that he replaced the comet by a star. This collision theory has recently been revived, with further modifications, by Jeffreys. Although his views call for further discussion and critical examination, it is difficult to see at present how they can possibly be reconciled with the similarity of the systems of Jupiter and Saturn to the main system. Grant for the sake of argument that a big splash formed the planets, then it seems quite beyond the bounds of probability that two smaller, but otherwise almost exactly similar, splashes should occur to create the systems of Jupiter and Saturn.

I believe I was the first, in 1901, to consider the possibility of the second body not colliding with the sun, but producing planets by tidal action. In 1904, Profs. Chamberlin and Moulton independently considered the same possibility, and developed it, along lines of their own, much further than I had done. They imagined that a series of solar eruptions, such as normally cause prominences, were so intensified by the tidal action of a neighbouring star that the ejected matter was projected clear of the sun's gravitational field, where it condensed into small solid bodies, which they designated as 'planetesimals'. These in turn underwent further aggregation and in due course formed the planets.

The scheme which they propounded seemed to me to be open to many objections. Not only did it fail to explain why the satellite systems of Saturn and Jupiter should resemble the main planetary system, but also it failed to explain why satellite systems should exist at all. Indeed, it is doubtful whether it can even explain the existence of the planets. Puffs of gas such as Profs. Chamberlin and Moulton imagined to condense into planetesimals would not condense into solid bodies at all. They could not do so inside the hot atmosphere of the sun, and as soon as they got clear of the sun's atmosphere they would merely scatter into space, like the leak of gas from a gas-burner. Calculation shows that any body of gas will do this unless it is of enormously greater mass than the supposed planetesimals. The mutual gravitational attractions of the molecules of a mass of gas of planetesimal dimensions would be too small by a factor of several millions to result in condensation in opposition to the ordinary gas pressure resulting from the kinetic energy of their motion.

Because the planetesimal theory seemed open to these and other fatal objections, I tried to trace out mathematically the course of events which would actually occur when a second star approached to within a specified distance of the sun and passed on its course without an actual collision taking place. Discarding all physical assumptions as to solar eruptions and the formation of planetesimals, I found that my own old conception of tidal action was able of itself, without any adventitious assumptions, to give a plausible account of the origin of the solar system. In this way I was led to propound a new theory of the origin of the solar system in 1916, which was very different from that of Chamberlin and Moulton.

The researches of Roche (1850) had already shown that every large mass such as the sun is surrounded by what may properly be described as a 'danger-zone'. No body of moderate size can revolve permanently inside this danger zone; it is rapidly broken up into minute pieces. Roche suggested that Saturn's moons and rings provide an example of this; the moons are all outside the danger-zone, but the rings are just inside, whence it is generally believed that the rings are the broken fragments of what was originally an ordinary moon of Saturn. There are good reasons for conjecturing that the system of asteroids which surrounds the sun forms a second illustration of the same effect.

Mathematical investigation of the tidal action between two stars showed that this concept of a danger-zone is equally applicable when two bodies merely approach one another temporarily and then pass on their respective courses. Two bodies which remain always at more than a certain distance from one another merely raise tides like those which the moon raises on the earth. As their distance lessens the height of tide increases; as it increases again the tides fall, until finally both bodies are left in their original undisturbed state. But if the two bodies approach to within a certain critical distance of one another, the whole character of these tides changes. Instead of a small elevation travelling over the surface of the disturbed body, as ocean tides travel over the surface of the earth, we have a huge mountain of gaseous matter which continually increases in height as the bodies approach, and finally shoots out to form a long arm which may finally, if conditions are favourable, establish contact with the second body. The two bodies will then be joined by a filament of gas, much as the two ends of a dumb-bell are joined by the handle of the dumb-bell. Under other conditions contact may fail to be established, and a long filament of gas will be left projecting from the primary body in the direction of the secondary body. It can be shown that this filament must inevitably, as the result of the mutual gravitational attractions of its own molecules, condense into detached masses. We can even calculate how massive these condensations will be. No great accuracy is possible, but we find that such condensations would at least be of the same general order of magnitude as the actual planets.

Before condensation commenced, the filament would be shaped like a cigar or a torpedo; one of the two pointed ends is the peak of the tidal mountain, the other is the last thin dribble of matter which came off just as the gravitational pull of the receding star was failing. After condensation we should expect to find the largest condensations near the centre, where the matter was originally richest, with the size of condensations tailing off at either end.

This exactly represents the present arrangement of the planets. It explains why the central planet Jupiter is the largest, and why the sizes and the weights of the planets both show a general tendency to fall off as we recede from Jupiter in either direction. The discovery of Pluto, which is, I suppose, quite certainly less than Neptune both in size and weight, has recently provided welcome confirmation of this prediction of the theory. It is perhaps also significant that, on the whole, the densest planets are not the most massive planets, in which we might reasonably have expected to find the matter most tightly packed, but those which lie nearest to the sun, although these are of comparatively small weight. These came from the root of the tidal mountain, and it seems possible that the heavier elements were more abundant here than at the peak of the mountain. The puzzlingly low density of Saturn, only one-eighth of that of the earth, is at once explained if we suppose that Saturn was formed mainly out of the higher strata of the sun's atmosphere.

We can, however, elaborate the theory in much greater detail than this. The planets at present move in orbits which are almost circular, but this must inevitably result from their having ploughed their way, for thousands of millions of years, through the dust and debris of space. When the planets first condensed they would be describing quite erratic, and indeed almost random, orbits about the sun. Their orbits could scarcely be expected to show any regularity beyond that of all lying in the plane of motion of the passing star which had brought them into being. Those planets which passed near enough to the sun would enter its danger-zone and be broken up in turn, just as the sun had previously been broken up by entering the danger-zone of the other star; the plane of their motion would be that containing the orbit of the planet round the sun. In this way we get a conjectural explanation of the satellite systems of the planets, of their general resemblance to the main system, and of the fact that their orbital planes lie mainly in the plane of the solar system.

In time the planets would cool, then liquefy, and then solidify; the largest would remain gaseous for longest. Now a theoretical investigation of the question shows that planets which remained gaseous until after the birth of their satellites would be likely to give birth to a large number of small satellites, whereas planets which had already liquefied or solidified would be likely to give birth to a smaller number of large satellites—or possibly to no satellites at all. This at once explains a further regularity in the arrangement of the solar system. The planets which have the greatest number of satellites are the two big central planets, Jupiter and Saturn. These have nine satellites each, and all are very small in comparison with the planets round which they revolve. Like the main solar system, the satellite systems of Jupiter and Saturn show the characteristics to be expected in systems born out of a gaseous body. As we proceed away from these giant planets in either direction we come to planets whose satellites are fewer in number, but larger in size relative to the sizes of their primaries—the characteristics to be expected in systems born out of a liquid, or liquefying, body. This is at once explained if we suppose that the great size of Jupiter and Saturn caused them to remain gaseous for a long time, while the smaller planets such as Mercury and Venus liquefied or solidified almost at once. The cases of transition appear to be provided by our own earth in the one direction and by Neptune in the other; each of these planets possesses a single satellite which is abnormally large in comparison with the size of its primary.

We can perhaps find confirmation of this in the fact that Mars and Uranus, the two planets which come next to these as we pass inwards towards Jupiter, are both abnormally small; we might have expected Mars to be intermediate in size between the earth and Jupiter, and Uranus to be intermediate in size between Neptune and Saturn. Now if we suppose that these two planets were the smallest of all the planets which retained their gaseous condition for long, they would suffer more than the others from the continued dissipation of their atmospheric layers into space. On this view Mars and Uranus must be regarded as mere relics of far larger masses, and we see at once why they are abnormally small for their positions in the planetary sequence.

There are so many conjectural elements in this theory that it would be rash to claim, or even to hope, that it can in any way prove final. The highest claim I would make for it is that it accounts for many of the observed facts, and has not yet been found to suffer from insuperable objections—and this can be said of few, if any, other hypotheses as to the origin of the solar system.

If we accept it we must accept also the consequences I stated at the outset. Stars are very rare objects in space, and so are spaced very far apart, so far apart that it is very hard to imagine the sparseness of stars in space. If we take three particles of dust and place them in a large cathedral, this would be incomparably more crowded with dust than space is with stars. As a consequence stars approach one another very rarely, and it is an almost inconceivably rare event for two stars to come so close that planets are born. Planets, and so presumably life also, must be exceedingly rare in the universe.

We can regard this with satisfaction or the reverse, as we choose. Some will feel overwhelmed with a great loneliness; they will feel that it adds to the terror which overcame Pascal when he contemplated the immense voids of space. Others will view it with satisfaction, because it adds to the relative importance of human and terrestrial life. When we thought of each star as the centre of a system which teemed with life, human life appeared as a very small thing; it formed an inconceivably small fraction of the total life of the universe. The new view compels us to think of life on earth as forming a comparatively large fraction of all life of the universe.

George Graham, F.R.S., 1673–1751.

ON Nov. 24, 1751, at night, a funeral procession left a shop bearing the sign of the Dial and One Crown, in Fleet Street, for Westminster Abbey. The hearse was preceded by three coaches containing the pall-bearers Dr. Knight, Mr. Watson, Mr. Canton, Mr. Short, Mr. Catlyn, and Mr. Bird, and was followed by nine other coaches. Thus was borne to his last resting-place George Graham, widely known both at home and abroad as the finest mechanician of his day. Arrived at the Abbey, the coffin was carried into the nave and was then laid beside that of Thomas Tompion, who had died in 1713, recognised as "the father of English watchmaking". The grave is not far from that of Newton. It is covered by a stone with an inscription, a part of which refers to Graham, "whose curious inventions do honor to ye British genius whose accurate performances are ye standard of mechanical skill". In the middle of the eighteenth century burials in the Abbey were more frequent than they are to-day, and it was a fortunate decision which led to the interment within its walls of these two famous masters of horology.

Graham, who was a Quaker both by upbringing and by conviction, was cast in much the same mould as that other Quaker and man of science of a later day, John Dalton. Born in Cumberland in 1673, at the age of fifteen he came on foot to London and there began an apprenticeship of seven years with Henry Aske, a clockmaker. His