JANUARY 15, 1932 PHYSICAL REVIEW VOLUME 39

ON THE ORIGIN OF THE SOLAR SYSTEM

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(Received November 18, 1931)

Abstract

A new account of the formation of the solar system, based on the rotational evolution of a single star, is given which describes the system in some detail and avoids the major difficulties encountered by earlier investigators. Electromagnetic effects have been shown by the author to permit the angular velocity of a star to increase until the star breaks into two components of comparable mass. The component stars are thermally asymmetrical and momentum is radiated more rapidly from the hot face than from the cool. This important new effect, which is quantitatively satisfactory, adds kinetic energy and angular momentum to the companion stars (in a manner analogous to the mechanism of a skyrocket) and may operate to separate the stars to infinity. Applying this to the solar system, the parent semiliquid sun is supposed to have divided and lost its companion. While each companion was inside the Roche limit of the other centrifugal and tidal forces broke off the planets. These in turn immediately broke up and formed the planetary satellites. Tides and tidal couples transferred the momentum of axial spin of the two component stars to that of orbital momentum, while the planets because of their small size largely escaped the effects of this process. Planetary rotations play an important role in the theory. The account replaces the earlier improbable and "accidental" theory by a systematic evolutionary process which is probably quite common in the Universe.

It has become increasingly clear during the past few years that the collision theory of the origin of the solar system, according to which the planetary system was formed by a highly improbable accidental collision of another star with our sun, faces difficulties which are perhaps nearly as serious as those which made the older nebular hypothesis untenable. The collision theory, which follows more or less closely a suggestion by the French naturalist Buffon, has been developed by Chamberlin and Moulton,[1], by Jeffries,[2] and by Jeans.[3] It takes two general forms, one in which it is considered that the close approach of a passing star to the sun raised tidal filaments and communicated sufficient angular momentum to them so that they did not fall back into the sun, but condensed and formed the planets; the other, proposed by Jeffries, considers that an actual glancing collision occurred between the visiting star and the sun. Jeffries' hypothesis, despite its assumption of a highly improbable particular glancing collision, is perhaps more satisfactory in that it at least offers the possibility of explaining the rotation of the planets, whereas the original form failed in this important respect. Calculation shows the probability of even a close approach of two stars to be so low that perhaps only one such occurs in the whole history of the Universe. There are other

[1] T. C. Chamberlin, Origin of the Earth.
[2] H. Jeffries, The Earth.
[3] J. Jeans, Astronomy and Cosmogony.

serious objections to the collision theory, as a reading of the works of the above investigators will show. Among these are the qualitative nature of the theory and hence the absence of verifiable deductions, and the inability of the theory to explain adequately some of the noteworthy characteristics of the planetary system.

Characteristics of the Solar System

The solar system is evidently not an accidental aggregation of stray bodies captured by the sun, and it seems clear that the entire system, with perhaps an occasional exception, must have had a common origin. The most noteworthy of the regularities and characteristics which must be accounted for in any complete theory of the origin of the system may be enumerated as follows:

(1) The direction of revolution of all the planets is the same.

(2) The orbits of the planets lie in nearly the same plane.

(3) The planetary system is dispersed over a region very large compared to that occupied by the sun, while the planetary satellite systems are relatively condensed.

(4) The equator of the sun lies nearly in the orbital plane of the planets.

(5) As far as is known, the axial rotations of the planets, save for one of the outermost, are in the same direction as their revolution.

(6) Except for the sun, and the two innermost planets, which have been particularly subject to tidal effect, the periods of axial rotation of all the planets are comparable.

(7) The period of axial rotation of the sun is comparatively large (31.8 days) and its angular momentum is but one thirtieth of that of the entire solar system.

(8) The massive planet Jupiter has more than half of the angular momentum of the system.

(9) Most of the planets have systems of satellites.

(10) The more massive and less dense planets have the greatest areal velocity.

(11) The orbital eccentricities of the planets are small, while those of some of the asteroids are large.

A detailed account of all the peculiarities of the solar system is manifestly impossible at the present time; for one cannot include the possibility that satellites may be transferred to other primaries or that asteroids may become satellites. Nor can one explain the peculiar numerical relations that have been found to describe the positions of the planets, satellites, etc., which relations are probably determined by conditions of stability and are believed to have no real significance in connection with the origin of the solar system. But we can, by a simple rotational theory, explain most of the above characteristics. Rotational hypotheses have been advanced by earlier investigators and we are aware that many statements are to be found in authoritative literature to the effect that "it has been proved" that the solar system could not have originated by rotational evolution. We show in the following paragraphs that these highly arbitrary opinions are based on insufficient evidence.

The present account of the genesis of the solar system depends essentially upon the rotational instability of a parent star which breaks up, forming two components of comparable mass, one of which is assumed to recede to infinity. On account of the frequent occurrence of binary stars the process of division seems quite common, and if a planetary system results each time that a star divides, many of these systems must exist within our galaxy. The solar system, therefore, instead of being a curiosity of the Universe resulting from an "accident," may well be the result of a regular and well organized plan of evolution. The following examination of events, in common with all others, is necessarily only roughly quantitative in nature and in minor details will undoubtedly need revision as more and more astrophysical data become available. Because we must necessarily neglect the density distribution functions inside the sun and planets, as well as assume that the bodies act as if they were composed of semi-liquid material, we rest content if we can show that the quantities are of roughly the right magnitude and that no inconsistencies of available energy, momentum, etc., result.

Evolution of a Rotationally Unstable Star

Under the above title the author has shown[4] that electromagnetic effects operating in the atmosphere of an energetic star permit the angular velocity of the star to increase until the star becomes rotationally unstable. A cataclysm results and the star divides into two components of nearly equal mass. Tides and tidal moments orient the two companions and cause the angular momentum of rotation to be largely transferred to that of orbital revolution. Thus the act of fission is essentially a stabilizing mechanism, because the axial rotations of the components are greatly reduced and there is no tendency for the separate components to break up again as a result of rotational instability. The two companion stars, after fission, are thermally asymmetrical, for one face of the star has just emerged from the depths of the parent star, while the other face is relatively undisturbed by the act. Radiation from the hot face is greater than from the cool one and since radiation carries off momentum there results an asymmetrical loss of momentum from the star. The reacting momentum gained by the star proper adds kinetic energy to the star and angular momentum to the pair in a manner analogous to that of a skyrocket or pinwheel. The kinetic energy added to a star by the mechanism is readily calculated; it is found that a typical energetic star will have sufficient energy added to it for the star to escape completely from the gravitational effects of a similar companion star if it radiates from one hemisphere an excess mass amounting to only 0.0003 (0.03 percent) of its total mass. This suggests that most of the single dwarf stars in the Universe have perhaps been formed by the division of more massive stars at some period in their life. In particular, our sun is well advanced in the course of stellar evolution and,

[4] R. Gunn, Phys. Rev. **39**, 130 (1932).

if the act of division is at all common to stars, our sun probably has passed through the process of division from a parent star and lost its companion.

The crucial difficulty of all rotational hypotheses concerning the solar system, first pointed out by Fouche,[5] was to account for the relatively slow rotation of the sun and at the same time account for the tremendous orbital angular momentum of Jupiter. The angular momentum of the parent star was known to be quite ample for all purposes; but by what mechanism could a large fraction of it be transferred to a satellite while the parent star retained practically none? Our present mechanism gives a definite answer to the question. When two bodies like our two companion stars separate, tidal couples convert the angular momentum of axial spin to that of orbital revolution, and the axial spin of both components decreases to small values. In an immediately preceding paper[4] we pointed out that inside the Roche limit the tides are tremendous, and this process probably takes place very rapidly. Indeed, astronomers seem generally agreed that the periods of rotation and revolution of close binaries are identical. Thus on our new hypothesis we should certainly expect the angular momentum of the sun to be small compared to the orbital momentum of the system. This agrees precisely with the observed facts.

According to Darwin's calculations the critical angular velocity ω_c of a rotationally unstable star of uniform density is specified by

$$\frac{\omega_c^2}{2\pi\gamma\rho} = 0.141 \qquad (1)$$

where γ is the gravitational constant and ρ is the mean density. Moreover, the critical angular momentum Ω_c is given roughly by

$$\Omega_c = 0.4 M_s a^2 \omega_c \qquad (2)$$

Substituting in these relations values appropriate to the sun, we find the critical period of rotation to be 6 hours, while the critical angular momentum approximates 11.2×10^{50} gm·cm^2 sec^{-1}. The angular momentum of the entire solar system is but 3.3×10^{50} gm·cm^2 sec^{-1} so that, even in the absence of other mechanisms, the unstable parent star had more than sufficient angular momentum to produce the solar system. It is, perhaps, significant that the angular momenta of the planetary system and that of a critically rotating parent sun should be of the same order of magnitude.

Observations show that the period of rotation of all the planets, except the two inner ones which have been particularly subject to tidal development, have effective periods of rotation systematically very close to the critical solar period of six hours. Thus the major planets, Jupiter, Saturn and Uranus all rotate about once in 10 hours. The axis of Uranus is tipped about 97° to the orbit (presumably by a resultant tidal couple acting, for a short interval of time just after birth, about an axis different from the axis of spin) and its rotation is retrograde, while Neptune, rotates once in 15 hours. The pres-

[5] Fouche, Comptes Rendus **99**, 903 (1884).

ent period of rotation of the earth is 24 hours, but its initial effective value must have been only 4.1 hours; for originally the moon was at the earth's surface and the angular momentum of the earth proper must have been correspondingly much larger than its present value. In addition to the earth it is known that Eros spins with a period of 5-1/4 hours. Mars is an exception, as it should be, for there are good reasons for believing that it has lost a comparatively massive satellite, and that this possessed most of the angular momentum of the Mars-satellite system.

This bracketing of the solar critical period by the effective periods of all the planets, which we should expect to yield useful information, is perhaps the most significant of all the data we have to consider. It is a remarkably clear guide that can lead the investigator to but one conclusion. *The planetary system originated as a result of the rotational break-up of a parent star not greatly different from our present sun.* Putting the matter another way: only a most extraordinary accident would arrange the initial periods of axial spin of all the planets so that these periods were always small multiples of their critical periods of rotation.

We have, of course, neglected the effect of tidal couples and condensation on the periods of rotation of our newly formed planets; but we can advance arguments to show that these could not have greatly altered the magnitude of the rotational period from that of the parent sun. For example, we know from observed tidal data that the tidal angle of the earth is very small, and that it almost immediately accommodates its form to external systems of forces. Thus tidal couples acting on the earth during the birth process were probably not large and we infer that such will be the case for the other planets, but rough calculation show that this certainly would not be true for the massive companions. Moreover, the major planets could not have condensed greatly since the time of their formation and hence their periods cannot now be much less than their original value. The tiny satellites of Saturn, which were born simultaneously with the planet, must have cooled off almost immediately after their formation; and if Saturn has condensed appreciably from its original state, then all the satellites inside the *original* Roche limit should have disintegrated to form systems of rings. It is known that the limit between the ring system and the satellite system corresponds with really surprising accuracy to the present Roche limit of Saturn. This appears to be reliable evidence for believing the entire solar system was practically condensed when formed. We therefore need not face the very serious difficulty of earlier theories which must account for gaseous condensation onto discrete nuclei of initially very small mass.

If we are incorrect in assuming that the satellites of Saturn were formed at its birth, then we cannot insist that the parent sun was at all like the present one. Indeed, it would be quite consistent with our present account to think of the parent sun as a massive B type star of comparatively low density and large radius which broke up and rapidly evolved into two far denser bodies. If this type of star were the parent of our solar system and if it yielded a satellite system whose densities are comparable to that of the present sun, then the rotational periods should correspond roughly to the sun's critical period. Thus no definite statement can be made regarding the properties of the parent star, but such evidence as is available indicates that it was not greatly different from the present sun.

Birth of the Planets

The parent sun rotated on its axis with increasing rapidity until rotational instability set in. A great cataclysm resulted and the parent star divided forming two companion stars of comparable mass. While the two companion stars were each well within the Roche limit of the other, tidal, gravitational, and

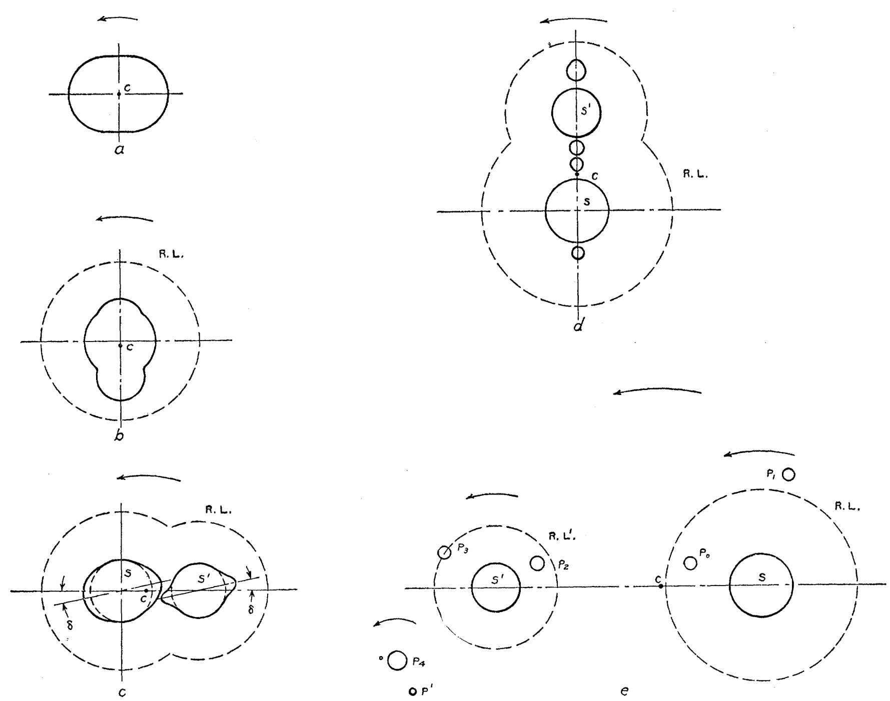

Fig. 1.

centrifugal forces were unbalanced in the regions of the inside and outside surfaces of the pair, so that the companions disintegrated in these special regions and produced the planets. These, in turn, while still inside the Roche limit of the parent star, broke up and formed the planetary satellite systems.

The history of each mass after it had been detached cannot be given in detail because its motion depended in a complicated manner on the mass ratio of the component stars, on the instantaneous positions of the planet relative to them both, and on the rate at which both stars lost their mass by radiation from the newly exposed hot face.

An idealized diagram of the process of formation is shown in Fig. 1. In this figure ***a*** represents the approximate configuration of the star just before rotational instability sets in. In ***b*** the process is well under way and in ***c*** the star has divided, tides are raised on each component, and tidal couples are transferring the angular momentum of axial spin of both components to that of orbital revolution. The approximate Roche limit for a non-rotating star is indicated by dashed circles in each case. In ***d*** parts of the tidal bulge indicated in **c** have broken off as a result of tidal and centrifugal forces and formed the planets. By this time the center of gravity of the system **c** has moved outside the sun S, and the path of the planets (assumed to have uniform surface temperatures) becomes complicated. The satellite systems of the planets are immediately formed and sometime later the system approximates that indicated in ***e***. Some of the planetary masses have fallen back into the sun; some, such as P_0, deficient in angular momentum, cannot get outside the Roche limit and are broken up and eventually dispersed, while others, like P_1, might develop into one of the innermost planets. Both companions have kinetic energy and angular momentum added to them by radiation reaction forces. The exposed areas and effective surface temperatures of both hot faces initially are the same so that the rate of loss of momentum by radiation is the same for each. Thus, at first, the accelerations of the stars are nearly inversely proportional to their respective masses and the stars separate from each other with constantly increasing velocity. The companion sun S^1 starts out with its family of satellites, P_2, P_3, etc., in an orbit about the sun, but it is constantly accelerated by non-central forces and calculations show that this acceleration may quite reasonably exceed the gravitational acceleration of the planets. In favorable parts of the planetary orbits the companion star, due to its constantly increasing velocity, loses gravitational control of the planet while the sun proper, due to its smaller non-central acceleration and greater mass, retains control and the planet finally revolves about it. The net result of the process is that a number of planets are strung out through space, perhaps to infinity; these have considerable angular momentum about the sun and they are necessarily many solar radii distant from the sun. By quite reasonable special hypotheses, additional details of the solar system, such as the comets, can be accounted for.

We may therefore think of the solar system as being almost completely formed when it was still condensed into a relatively small space where tidal forces were important, and may attribute its present open structure to the asymmetric loss of mass by radiation. Thus the net result of our rotational cataclysm is a very disperse system of two slowly spinning stars and a system of planets and planetary satellites. All bodies of the system revolve in the same direction and in the same plane and spin on their axes with an angular velocity comparable to that of the parent star. One star is eventually lost to infinity and the solar system, as we know it, results. Our planets, therefore, are simply the disintegration products of a great cataclysm.

The Satellite Systems

During the time that the planets were still inside the Roche limit of their respective primaries, tidal and centrifugal forces broke off the planetary satellites. The planets were probably largely liquid when formed, and because of the relatively small size and high density of the minor planets, they largely escaped during the birth process the loss of angular momentum of spin due to tidal couples. For example, the rotational period of the earth before it lost the moon was 4.1 hours, while its critical period according to Eq. (1) was very close to this, or 3.3 hours. Thus when the earth was inside the Roche limit of the companion stars we might well expect a breakup which shared some of the characteristics of both rotational instability and tidal instability. If the break-up were purely rotational, the component masses would be comparable in size; if tidal, the masses would differ greatly in size. A break-up due to both causes might be expected to produce satellites of intermediate size. Qualitatively this agrees with the observed Earth-Moon mass ratio, and we may hope to obtain in the future more useful information by considering the mechanism in greater detail.

After the moon was actually detached from the earth, tidal couples rapidly transferred the moon's angular momentum of spin to that of orbital momentum and the earth is still losing and transferring its angular momentum by the same means. This process adequately accounts for the present position of the moon and the fact that its period of axial rotation corresponds to its revolution.

It seems possible that a similar division of the other minor planets took place. Mars is deficient in angular momentum according to our present account, and it seems quite probable that it has lost a fairly massive satellite which perhaps broke up and formed the asteroids.

Because of the small size of the planets, the surface temperatures were probably nearly uniform so that radiation reaction forces were comparatively small. Hence the positions of the satellites were largely determined by their initial momenta and therefore the planetary satellite systems are quite compact. Satellites which have transferred to other primaries will revolve in remote orbits and we should expect that retrograde satellites would be so placed. Tidal couples acting on the major planets produced angular accelerations which were probably greater than those of the minor planets so that they were rotationally stable after birth and produced only small tidal satellites which necessarily revolved only in the forward direction.

Remarks

We do not attempt to discuss here various earlier theories of the origin of the solar system, the earth-moon system, etc., because these are all adequately discussed in available texts. The problem of the eccentricity of the orbits in the new theory cannot be definitely solved without greater attention to detail. It seems quite possible that the initial eccentricities were nearly as low as that of the present orbits since our special mechanism after break-up adds angular momentum to the system. In any case, the present account is superior in this respect to any of the older ones; for it too can assume a resisting medium even though this seems a most unsatisfactory artifice. We can account for the observed differences in the density of the major and minor planets by suggesting that the major planets were born from the outer layers of the parent star while the minor planets were born from the hotter inner regions; however, the evidence for such an explanation is not clear cut and the suggestion is only tentative.

Many features of the solar system remain to be examined; but the foregoing account describes our system in some detail and definitely removes the objections of earlier investigators to a theory postulating evolution from a single rotationally unstable parent star. The entire account could be given equally well without the introduction of radiation reaction forces if we were to assume that the companion star was captured and carried away by another star. This event, although relatively improbable, is far *more* probable than an actual close collision of two stars; for, the collision would be a three-body collision of an open pair and the momentum conditions could be readily satisfied.

In an immediately preceding paper which should be read in connection with the present one, the author discussed the fission theory of binary star systems and showed that the theory was entirely consistent with observation if the stars' electric and magnetic fields and the effects of radiation reaction forces were considered. Binary stars are very common in the Universe, and the process of fission probably takes place at least once in the history of each star. Thus it seems probable that many planetary systems exist, some with one sun, some with two, and occasionally one with several close stars of the same system. Whether life as we know it exists on these planets must long remain unanswered; but conditions on many of them must be comparable to those existing on the earth. It seems clear that the solar system was not the result of a highly improbable accident and the presence of man upon the earth a still greater one, but the complete organization was brought about as the result of a definite orderly and evolutionary plan. According to our series of investigations the course of evolution was largely guided by the electric and magnetic forces that act on the ions of a star's atmosphere.