

THE ORIGIN AND EVOLUTION OF THE SOLAR SYSTEM

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Summary

Various theories are reviewed. By eliminating ideas which appear to be faulty, by accepting ideas which appear to be sound and helpful, and by introducing some new ideas to fill the gaps, the outline of a complete theory is built up.

The only mechanism that appears to be capable of explaining the regularities of the solar system is fluid friction, and it is inferred that the material which now forms the planets and their satellites existed at one time in the form of a vast rotating disk. Bodies of planetary mass cannot be formed by condensation in a cloud of gas, and small solid particles must have been the chief ingredient in this primitive material. The angular momentum of the disk is explained quite simply by the assumption that the material was collected from interstellar space, and this is the only explanation that gives a result which is numerically of the right order.

Condensations would form in the rotating disk, and in the first instance these would be small and numerous. Subsequently they would coalesce to form a single large cluster in each region of interplanetary space. Each cluster would consist of a nucleus and a surrounding disk or annulus. Owing to the combined effect of viscosity and tidal friction, there would be a loss of angular momentum and the bulk of the material would be absorbed by the nucleus to form the planet. The residue of material in the annulus would condense to form the satellites.

In the region which lies immediately inside Jupiter's orbit the perturbations caused by the planet would drive much of the material inwards towards the Sun. In the attenuated residue the condensations would be smaller and more numerous than usual; they would coalesce to some extent, but not sufficiently to form a single planet, and the result would be the formation of the group of small bodies we know as the asteroids. In the region outside the orbit of Neptune the material would also be highly attenuated, and here again condensations would be small and numerous, but the progress of evolution was slower, and the region is probably populated by a very large number of small clusters. Wandering clusters make their appearance from time to time as comets.

Introduction

1. The paper is based on the assumption that there is sufficient knowledge available to permit of the construction of a complete theory of the origin and evolution of the solar system, provided that the information is carefully sifted and properly utilized. Helpful ideas must be retained, faulty ideas must be eliminated and gaps in the resulting theory must be carefully filled.

2. A complete theory necessarily raises a number of questions of a controversial character and a full discussion would need a book rather than a paper. Moreover, the various digressions that would be involved in this method of approach would tend to obscure the main argument. In order to present a clear picture of the whole process, therefore, detailed discussion of particular issues will be avoided, on the understanding that the argument can be expanded on some future occasion if required.

PART I. *The regularities of the system and their significance*

3. The planets revolve about the Sun in the same direction and in nearly the same plane, and these and other regularities of the system are much too remarkable to be due to chance. They must be ascribed to the existence of some common cause (Laplace).*

4. The only mechanism that is known to be capable of creating the required regularity is fluid friction, the term fluid being taken to include a cloud of small solid particles as well as a cloud of gas. The inference is that the material that now forms the planets and their satellites existed at one time in the form of "a fluid of immense extent" (Laplace). The alternative hypothesis that the regularities were produced after the appearance of the embryo planets is rejected for reasons which are set out below.

5. The bulk of the materials of which the Earth is composed are such that they would necessarily assume the solid state at the temperature of interplanetary space, and this statement is no doubt true also of the other terrestrial planets. There is the further point that condensations of planetary mass cannot be formed in a gas.† For these reasons it may be inferred that the material out of which the planets were originally formed consisted of small solid particles.

6. Although a cloud of small solid particles was the essential ingredient out of which the planets were first formed, gas must also have been present. When the major planets reached a certain size they captured gas as well as other materials.

7. The angular momentum of the planets must have been derived from one or more of three sources: from the Sun, from some external source, or from the original material.

8. Viscous friction would provide a mechanism capable of transferring energy and angular momentum from the Sun to a surrounding cloud of fluid, but calculation shows that it could not be responsible for the transfer of an adequate amount in the available time.

A theory was put forward a short time ago by Alfvén in which it is suggested that electromagnetic forces might take the place of viscous friction‡, but the possibility that such a process might be significant remains to be demonstrated.

9. The theory, which has sometimes been put forward, that a planet might be born ready-made from the Sun (or a satellite from a planet) is untenable. Firstly, because a body ejected from the Sun would not possess sufficient angular momentum to establish it in a planetary orbit; secondly, because an explosion capable of ejecting the material would not eject large masses, but would scatter the material in all directions.

10. The nebular theory usually associated with the name of Laplace postulates that the Sun and the planets were condensed from the same rotating cloud of gas. The theory is untenable because the angular momentum per unit mass of the planets differs much too widely from the angular momentum per unit mass of the Sun.§ The inference which must be drawn from the facts is that the formation of the Sun and the formation of the planets were two distinct events which occurred at different times and were based on different sources of material.

* *Exposition du Système du Monde*, Paris.

† K. E. Edgeworth, *M.N.*, **106**, 473, 1946.

‡ A. Hunter, *Nature*, **156**, 378, 1945.

§ The first writer to direct attention to the importance of angular momentum in relation to theories of planetary evolution was M. Babinet, *Comptes Rendus*, **52**, 481, 1861.

II. Collision theories represent an attempt to explain the dual origin of the material. They are open to the following objections* :—

(a) They lack plausibility. The number of collisions of the assumed type that have taken place since the formation of the stars is probably only a few hundreds.

(b) The filament which is supposed to have been formed as a result of the collision would not break up into ready-made planets but would disintegrate.

(c) The angular momentum of the planets (or material) resulting from the collision would be inadequate.

(d) The orbits of the planets which would be formed by this process would be highly eccentric.

(e) The angular momenta of the satellites about their primaries create difficulties of precisely the same kind as do the angular momenta of the planets about the Sun, but it is impossible to invoke special collisions for each of the planets. “The systems of Saturn and Jupiter are so like that of the Sun that any hypothesis which assigned different origins to the system and its sub-systems would be condemned by its own artificiality” (Jeans).†

12. The theory of a separate collision between two other stars, one of which was a companion to the Sun, appears to meet the objection that the angular momentum is insufficient, but it does not meet any of the other objections.

13. It has been suggested that the rounding up of eccentric orbits might have been brought about by the presence of a “resisting medium”, and the influence of this resisting medium has been compared to the influence exerted by the air in a clock-case on the oscillations of a pendulum. The analogy is false. The molecules of air in a clock-case are not absorbed by the pendulum and the air maintains its separate existence indefinitely. Small particles approaching a planet, on the other hand, would be absorbed. To be of any significance the mass of the resisting medium would have to be of the same order as the mass of the planets.

The questions then arise: what was the resisting medium? whence did it come? and what has happened to it? No serious attempts to answer these questions appear to have been made, and, if an attempt is made to answer them, we seem to be driven back inevitably to our original proposition that “the Sun was at one time surrounded by a fluid of immense extent”.

14. Other solutions having failed, we return to the assumption that the angular momentum of the planets was contained in the original material, and we postulate a vast rotating disk made up of separate particles each revolving about the Sun in its own orbit. To emphasize this aspect of the matter the individual particles may be referred to as “planetesimals” (Chamberlin and Moulton).‡ The rotating disk would resemble the rings of Saturn but on a much vaster scale.

15. Collisions between the particles are evidently of importance. At first they might be of considerable violence and the individual particles might be vaporized, but they would condense again.§ As time went on, random velocities would be reduced and collisions between particles would become elastic but not completely so; further reduction in the random velocities would occur and the disk would become very thin. We are again reminded of the similarity between this postulated disk of planetary material and Saturn’s rings.

* See Harold Jeffreys, *M.N.*, **108**, 94, 1948.

† J. H. Jeans, *Problems of Cosmogony and Stellar Dynamics*, Cambridge, p. 281, 1919.

‡ T. C. Chamberlin, *Ap. J.*, **14**, 17–40, 1901. Chamberlin and Salisbury, *Geology: Earth History*, Vol. II, 38–81, 1906.

§ A. L. Parson, *M.N.*, **105**, 244, 1945.

16. There is a very simple and obvious theory which can be offered to explain the origin of the planetary material, and it is surprising that it seems never to have been seriously considered.

It would be unreasonable to suppose that the formation of the stars involved the capture of the whole of the scattered material in interstellar space. At least a small residue would remain uncaptured, and this residue would be supplemented by matter ejected by stellar explosions. A star such as the Sun would eventually capture the stray material in its own neighbourhood, and this captured material would condense to form the vast rotating disk which has already been described.

Similarly it may be postulated that the process, whatever it was, that led to the formation of the planets did not absorb the whole of the available material. A residue remained which subsequently condensed to form the satellites.

17. The theory that the planetary material was condensed from interstellar space may be tested as follows. The volume of space occupied at the present time by a star such as the Sun is about 800 cubic light-years. At the time when the stars were formed it was probably about one hundredth part of this *, say 8 cubic light-years = 6.7×10^{54} cub. cm., equivalent to a sphere of radius 1.2×10^{18} cm. The orbital angular velocity of the Sun about the centre of the Galaxy is 10^{-15} , and the local angular velocity of a cloud of material would be about one-third of this. The surface angular momentum per unit mass of the supposed cloud of material in c.g.s. units is therefore 5×10^{20} , compared with 2.5×10^{20} which is the angular momentum per unit mass of the planet Neptune. It will thus be seen that the theory gives a value of the planetary angular momentum which is exactly of the right order, and it is the only theory which does so.

18. A small part of the material of the rotating disk was absorbed by the Sun, and this explains why the rotation of the Sun is in the same direction as the motion of the planets in their orbits.

19. The preceding sections appear to establish, beyond all reasonable doubt, that the planets were evolved from a vast rotating disk of scattered material, and that this material was originally derived by capture from interstellar space.

It remains to consider by what processes this rotating disk of scattered material condensed to form the planets and their satellites.

PART II. *The formation of the planets and their satellites*

20. This part of the paper starts with the postulate that the material out of which the embryo planets were first formed existed originally in the form of a rotating disk of small solid particles extending beyond the orbit of Neptune.

21. Any particular part of the disk may be stable or there may be a tendency to form local condensations.

Let R = distance from the centre of the primary,

M = mass of the system inside the radius R ,

$\bar{\rho}$ = mean density of the system = $3M/4\pi R^3$,

A = radius of the local region,

m' = mass of the material inside the radius A , and

ρ' = local density = $3m'/4\pi A^3$.

* K. E. Edgeworth, *M.N.*, **106**, 472, 1946.

Jeffreys * has shown that a local condensation cannot exist unless

$$\rho' > 0.022\bar{\rho}. \quad (1)$$

Maxwell's formula for the rings of Saturn † can be made to yield a similar result, that is to say

$$\rho' > 0.038\bar{\rho}. \quad (2)$$

Both formulae are open to the criticism that they involve an over-simplification of the problem. A more complete analysis would no doubt yield a different value of the numerical coefficient, although it could hardly alter the general character of the formula. Whatever the actual formula may be, if ρ' is less than the critical value, the disk is stable and the formation of local condensations is impossible. On the other hand, if the critical value is exceeded, condensations will be formed and will grow at the expense of the rest of the disk.

22. As a result of collisions between the particles, random velocities are soon reduced to a low figure and the disk becomes very thin. It will then be found that the condition defined by equation (1), or whatever the accepted formula may be, is satisfied, provided that the size of the condensation does not exceed a certain limit.

Let it be assumed that the area of the region from which each planet derived its material was $2R^2$.

Let N = number of condensations formed in this region, and m = mass of the planet.

Then it follows from equation (1) that

$$N = m/m' > 10^{-4} \times (M/m)^2. \quad (3)$$

Applying this formula to the case of Jupiter, the number of condensations needed to form the planet is found to be several hundreds; in the case of the Earth they would be numbered in millions. A different value of the numerical coefficient in the previous equation would involve a corresponding change in equation (3). In fact, however, the exact number of condensations formed is unimportant; the essential point is that they would be numerous and small in size.

It may be remarked in passing that the estimate of the number of condensations formed does not enter into our subsequent discussion as to the time required for the condensations to coalesce to form a planet, for the reason that the time required for the early stages is short in comparison with the total time.

23. The condensations that might be formed in the rotating disk would, in the first instance, be in the nature of eddies, that is to say they would maintain a definite structure, but the "fluid" would flow through them. They would be regions in which the local density was above the average.

Flow within the eddy would be subject to viscous friction, and the effect of the friction would be to cause the eddy to grow at the expense of the rest of the disk.

24. Eventually the central density of an eddy would increase sufficiently to make it possible for particles to move in closed orbits about the centre. This is equivalent to the condition that ‡

$$\rho' > 3\bar{\rho}.$$

The condensations may now be described as "clusters", and the central part of a cluster may be described as the "nucleus".

25. At first the clusters would consist simply of regions of high density embedded in a continuous sheet of material. With lapse of time, viscosity would cause the clusters to grow by absorbing material from the disk until the whole of

* Harold Jeffreys, *The Earth*, Cambridge, p. 15, 1924.

† K. E. Edgeworth, *M.N.*, 106, 481, 1946.

‡ K. E. Edgeworth, *loc. cit.*, p. 481.

the scattered material was absorbed, and the system would then consist of a number of individual clusters separated from one another by regions of empty space.

26. It is at this point that erroneous inferences appear to have been drawn as to the course of events. It has been assumed that the clusters would contract upon themselves, and that the final result would be, not a small number of large planets, but rather a large number of small planets such as the asteroids. It has therefore been argued that the planets could not have been evolved by a process of condensation from a rotating disk of scattered material, and other solutions have been sought. The argument is not valid.

27. There were in fact two evolutionary processes at work. The clusters did contract upon themselves, but at the same time they tended to coalesce, so that the average mass of a cluster increased. The course of events was determined by the relative importance of these two processes.

28. Following upon the absorption of the scattered material by the clusters, the size of a cluster is determined by its rotation, and contraction depends upon the dissipation of angular momentum, or more precisely on the transfer of angular momentum from the individual cluster to the system as a whole. The mechanism responsible for the loss of angular momentum is akin to tidal friction and may be described as such.

With tidal friction the magnitude of the effect declines as the radius of the cluster decreases, so that contraction proceeds at an ever decreasing rate.

29. The actual rate of contraction may be estimated as follows. When first formed, the boundary of a cluster may be identified with the boundary within which particles can move in closed orbits. This region is ellipsoidal, but for simplicity it may be regarded as spherical.

Let A = the radius of a cluster (as defined above), then

$$A^3 = R^3(m'/3M).*$$
 (4)

It is clear that inside the boundary the gravitational field is mainly due to the cluster itself; outside the boundary the field of the Sun is of dominating importance. It may therefore be said that the boundary itself defines a surface on which the attractions of the Sun and the cluster are of equal importance. Let it now be assumed that, under these conditions, the radius of the cluster is reduced by one per cent in each revolution; the precise figure is not of serious importance to our present argument, which would not be materially affected if our assumption were altered to 1 in 10 or 1 in 1000.

Let a = the radius of the cluster after time t .

It has been shown by Darwin † that the retardation due to tidal friction is inversely proportional to the sixth power of the distance, and it follows that it is also proportional to the sixth power of the diameter, since it is the ratio between diameter and distance that is involved in the argument. Combining these assumptions we get

$$\frac{dt}{da} = -\frac{100}{A}(A/a)^6 p,$$
 (5)

where p is the period of revolution at distance a . Now p is itself a function of a , that is to say

$$p = (a/A)^{\frac{3}{2}} P',$$
 (6)

* *Loc. cit.*, p. 481.

† G. H. Darwin, *The Tides*, London, p. 247, 1898.

where P' is the period of revolution at distance A . Remembering that the local angular velocity of the condensation is about one-half the angular velocity of the condensation in its orbit, we may write $\frac{1}{2}P' = P =$ the period of revolution about the Sun, so that

$$dt/da = -200a^{-\frac{1}{2}}A^{\frac{1}{2}}P, \quad (7)$$

$$t = 57(A/a)^{\frac{1}{2}}P, \quad (8)$$

$$a/A = 3(t/P)^{-\frac{2}{3}}. \quad (9)$$

This equation gives the rate at which a cluster contracts upon itself as a result of tidal friction due to the action of the Sun.

30. We must now turn to the question of stability in a system which consists of a disk made up of small clusters, each cluster being itself a disk of small solid particles. If Maxwell's analysis is applied to this type of structure, it is found to be stable, and any oscillations that may occur therein are of constant amplitude. It is necessary, however, to take into account certain factors which are not discussed in Maxwell's essay.

Until such time as scattered material between the clusters is absorbed, relative motion of adjacent clusters is subject to resistance due to viscous friction. If allowance is made for this damping, it would no doubt be found that the amplitude of the oscillations is no longer constant.

Clusters at different distances from the Sun move in their orbits with different angular velocities and the distance of a cluster from its neighbours is not constant, even if it is postulated that oscillations are originally absent.

In the long run close approaches between clusters lead to an increase in the random velocities.*

All these factors tend to increase the relative motion of adjacent clusters, so that collisions take place between one cluster and another. If the collision is slight the clusters may separate again, but, in the case of a head-on collision, the colliding clusters must coalesce. It will be assumed that in one in every five collisions the colliding clusters fail to separate again and coalesce to form a single cluster.

31. The rate at which clusters collide and coalesce depends on the random velocity and on the size of the clusters. For the purpose of numerical calculation the random velocity is assumed to be one hundredth part of the velocity of the cluster in its orbit. When two clusters coalesce the mass of the new cluster is the sum of the original masses, and it is assumed that equations (4) and (9) are still applicable and can be used to determine its radius. The rate at which the number of clusters is reduced by collisions may then be estimated as follows.

In our present problem the frequency of the collisions must be regarded as a problem in two dimensions rather than three, and the duration of the free path is of the order

$$\frac{0.2}{vn(2a)},$$

where $v =$ random velocity $= 0.01R\omega = 0.06R/P$,

$n =$ number of clusters per unit area $= N/2R^2$, and

$a =$ radius of the cluster $= 3R(m/3MN)^{\frac{1}{3}}t^{-\frac{1}{3}}P^{\frac{1}{3}}$,

so that the duration of a free path becomes

$$1.6(M/m)^{\frac{1}{3}}N^{-\frac{1}{3}}t^{\frac{1}{3}}P^{\frac{1}{3}}. \quad (10)$$

The number of collisions per unit time is the reciprocal of this multiplied by $\frac{1}{2}N$.

* K. E. Edgeworth, *M.N.*, 108, 417, 1948.

It is assumed that one collision in five causes the colliding clusters to coalesce, so that

$$\delta N/\delta t = -0.06(m/M)^{\frac{1}{2}}N^{\frac{1}{2}}t^{-\frac{1}{2}}P^{-\frac{1}{2}}. \quad (\text{II})$$

A solution to this equation is given by

$$t/P = 400(M/m)^{7/15}N^{-14/15}. \quad (\text{I2})$$

To obtain the time required to reduce the number of clusters from (say) 10^6 to one, we substitute these values for N in equation (I2) and we get

$$(t_2 - t_1)/P = 400(M/m)^{7/15}(1 - 0.0000025) = 400(M/m)^{7/15}.$$

$$\text{For the Earth } t/P = 1.5 \times 10^5, \quad t = 1.5 \times 10^5 \text{ years}$$

$$\text{Jupiter } t/P = 10^4, \quad t = 1.2 \times 10^5 \text{ ,,}$$

$$\text{Neptune } t/P = 4 \times 10^4, \quad t = 6 \times 10^6 \text{ ,,}$$

It is therefore clear that the clusters in any particular region will coalesce to form a single large cluster within a comparatively short time.

32. Our next problem is to explain how it came about that the vast rotating cluster of material got rid of its angular momentum and condensed to form a planet.

Throughout this phase the cluster consisted of two parts: the central condensed portion, or nucleus, and a rotating disk which may be referred to as the annulus. Broadly speaking, the explanation is that angular momentum was transferred outwards from the nucleus to the periphery of the annulus by viscous friction, and that, having reached the periphery, it was dissipated by tidal friction as already described.

33. At this stage in our analysis it is convenient to introduce the idea of opacity, which is defined as follows:—

Let n = the number of particles per unit area of the disk,

b = the radius of a particle,

q = the mass of a particle, and

σ = the mass of the disk per unit area.

The proportion of light that is intercepted by a layer of widely scattered material is πnb^2 , and this quantity will be called the opacity, irrespective of whether the disk is able to transmit light or not; it may be denoted by Q .

Now $\sigma = nq$, and therefore

$$Q = \pi b^2 \sigma / q. \quad (\text{I3})$$

For the purpose of numerical calculation it may be assumed that $b = 0.25$ cm., $q = 0.2$ g., which gives approximately

$$Q = \sigma,$$

and on this basis it is possible to prepare a table showing the approximate value of Q for the material which was destined to form the various planets.

TABLE I
Values of $Q = \sigma = m/2R^2$

Mercury	30	Jupiter	160
Venus	20	Saturn	13
Earth	13	Uranus	1
Mars	0.5	Neptune	0.2
Asteroids	0.001 (?)	Pluto	0.001 (?)

It will be observed that the values range from 160 for Jupiter to 0.2 for Neptune; Pluto must be regarded as an escaped satellite.

34. So long as the annulus remained sufficiently opaque, viscosity continued to be significant, and the outflow of angular momentum and the inflow of material continued. When the supply of material fell off, however, the value of Q decreased and viscosity decreased also. Eventually viscosity ceased to be effective, the inflow of material was checked, and the residue remained available for the formation of the satellites.

The approximate mean value of the opacity for the region in which Jupiter's larger satellites were formed, on the assumption that the radius of the region was about 2.5×10^{11} cm., would be about 10^3 . During the earlier period, while the planet itself was being formed, the opacity must have been higher.

35. The mechanism involved in the evolution of the satellites from the rotating disk of material surrounding the planet was no doubt similar to that involved in the evolution of the planets from the rotating disk of material surrounding the Sun, and calls for no special comment. At the same time it may be remarked that the evolution of the planets took place without external interference, with the result that the system exhibits a high degree of regularity, whereas the evolution of the planetary systems was subject to interference by the Sun, so that the smaller systems are less regular than the larger.

36. The inner satellites of Jupiter, Saturn and Uranus move in orbits which are nearly in the same plane as the rotation of the planet itself, from which it may be inferred that there was some close connection between the evolution of the planet and the evolution of the principal satellites. The theory set out in the previous sections explains why this was so.

37. The outer satellites of these three major planets are small and their orbits are retrograde. The small satellites constitute a special problem which will not be discussed here.

38. The evolution of the Earth and Moon also constitutes a special problem, which will not be discussed here.

PART III. *Asteroids and comets*

39. Reference must now be made to the case in which the opacity of the rotating disk is appreciably less than unity. The present mass of the asteroids suggests that the opacity of the original material was of the order 0.001 or thereabouts, but it is possible that an appreciable quantity of the original material has since been captured by some of the planets, so that the initial opacity may have been higher.

40. In a rotating disk, free from external interference, the random velocity of the particles might be so low that collisions would be practically eliminated. On the other hand, the orbits of the particles would be perturbed by the planets and random velocities would be increased. It is difficult to say therefore to what extent viscosity would be developed in a transparent disk in the region now occupied by the asteroids.

If the formation of eddies was possible, we may write as before

$$\rho' > 0.022\bar{\rho} \quad \text{and} \quad N > 10^{-4}(M/m)^2.$$

On the other hand, if the boundary of a condensation is identified with the region within which a particle can move in a closed orbit, we have

$$\rho' > 3\bar{\rho} \quad \text{and} \quad MN > 4.5(M/m)^2.$$

In the former case N is found to be of the order 10^{18} and in the latter case 10^{13} . All that can be said with certainty is that the condensations would be much smaller and more numerous than in the case of other planetary material.

41. In accordance with the argument developed in earlier sections of this paper the condensations or clusters would come into collision with one another and would coalesce, so that in the course of time the average mass would increase and the number would be reduced. Owing to the much longer time involved, random velocities would be higher and the problem of collisions must be dealt with in three dimensions, so that the duration of the free path is of the order

$$\frac{0.2}{vn(2a)^2},$$

where v = random velocity = $\frac{1}{2}z\omega = \pi z/P$,

z = half the thickness of the disk,

n = number of clusters per unit volume = $N/(4R^2z)$,

a = radius of cluster = $3R(m/3MN)^{\frac{1}{3}}t^{-\frac{1}{3}}P^{\frac{2}{3}}$;

so that the duration of the free path becomes

$$0.007(M/m)^{\frac{2}{3}}N^{-\frac{1}{3}}t^{4/3}P^{\frac{2}{3}}, \quad (14)$$

from which we obtain

$$\delta N/\delta t = -14(m/M)^{\frac{2}{3}}N^{\frac{2}{3}}t^{-4/3}P^{-\frac{2}{3}}, \quad (15)$$

and thence

$$t/P = 0.034(M/m)^{14/9}N^{-\frac{2}{9}}. \quad (16)$$

The mass of the asteroids is not known exactly, but M/m is probably of the order 10^9 . We may also write $t = 4 \times 10^9$, $P = 4$, and thus the number of asteroids at the present time is found to be

$$N = 1800,$$

which is a result of the right order. A disk of such small mass would not coalesce to form a single planet.

42. It would be unreasonable to suppose that the original rotating disk of scattered material came to an abrupt end outside the orbit of Neptune. There must have been a gradual thinning out of the material at the outer boundary. There is no definite evidence as to the opacity of this material except that it was insufficient to lead to the formation of a planet.

43. Comparing the clusters formed outside the orbit of Neptune with the asteroids, the chief point of difference is that the evolutionary process was much slower. The tempo of the process depends on the factor t/P , and the period of rotation P is about one hundred times greater in the former case than in the latter. Under similar conditions the process of evolution would be much less advanced and the clusters would be smaller and more numerous.

It is not unreasonable to suppose that this outer region is now occupied by a large number of comparatively small clusters, and that it is in fact a vast reservoir of potential comets. From time to time one of these clusters is displaced from its position, enters the inner regions of the solar system, and becomes a visible comet.

Conclusion

The analysis set out in the paper leads to the conclusion that there is no need to invoke some special and improbable coincidence, such as a stellar collision, in order to explain the origin of the solar system. On the contrary, the solar system can properly be regarded as a natural product of normal evolutionary forces.

*Cherbury, Booterstown,
Co. Dublin :
1949 June 3.*