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The Evolution of our Planetary System

By Lieut.-Col. K. E. Edgeworth, D.S.O., M.C., F.R.A.S.

Introduction

This paper was originally written at considerably greater length, but it has been cut down owing to the shortage of paper. In its present form it should be regarded not so much as a theory of astronomical evolution, but rather as the outline of a theory with many gaps in it which remain to be filled in on some future occasion.

The method of approach departs somewhat from that usually adopted. Instead of starting with some arbitrary hypothesis and attempting to show that it explains the facts of observation, the first step is to take note of certain observed facts and to draw from them certain inferences; these inferences are then used as a foundation on which the theory itself is erected.

Again, the problem of the galaxy and the evolution of the stars, the problem of the solar system and the evolution of the planets, and the problem of the planetary systems and the evolution of the satellites are not regarded as separate and distinct problems, but simply as phases in the larger problem of astronomical evolution. Thus the solar system is regarded not as the result of some special accident, but rather as the natural product of normal evolutionary forces.

In this connection we may quote Sir James Jeans: "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." *

The Initial State

The various astronomical bodies which go to make up the galaxy, the solar system and its sub-systems are all in a state of motion and are held together by gravitational attraction. The motion of any particular member of one of these systems can be described as consisting of two parts: a velocity of rotation (revolution) about the axis of the system and a random velocity peculiar to the body in question. The velocity of rotation is the velocity which the body would possess if it were moving in a perfectly circular orbit about the axis of the system; the random velocity is the difference between the actual velocity and the velocity of rotation.

Thus, the random velocity of a body moving in a perfectly circular orbit in the central plane of the system is zero; the random velocity of a body moving in an elliptic orbit has components at right angles to the axis of the system; and the random velocity of a body moving in an inclined orbit has a component parallel to the axis.

It is a characteristic feature both of the galaxy and of the solar system that the random velocities of the stars and planets are small compared with the velocity of rotation. To explain this feature it is necessary to suppose that both these systems passed through a stage of development in which the material of which they were composed consisted for a considerable period of comparatively small particles, and that random velocities were reduced by inelastic collisions.

It must be postulated therefore that stars, planets and other astronomical bodies have been evolved from a vast cloud of scattered material, and it may be supposed that this material consisted of a mixture of gas, dust and small solid particles. It is a characteristic feature of these clouds of scattered material that heat generated within them is converted into radiation and escapes into space.

As regards the size of the particles, it is known that the dimensions of hailstones formed in the Earth's atmosphere are of the order of a few millimetres, and that many of the meteorites which become entangled in the Earth's atmosphere appear to be of similar size. Where calculations are necessary, therefore, it is assumed that the average radius of a particle is 0·25 cm. and its average mass 0·2 gm.

* J. H. Jeans, *Problems of Cosmogony and Stellar Dynamics* (1919), p. 281.

Rotation of the Primitive Material

It is known that the galaxy is rotating and that the velocity of any particular star differs little from the velocity of rotation at which gravity is balanced by centrifugal force. Since the galaxy is isolated in space, its angular momentum must have remained substantially unchanged, and it must be postulated that the cloud of scattered material from which it was evolved was also rotating.

When a body is rotating with uniform angular velocity α, every part of it is also rotating with the same angular velocity and is endowed with local angular momentum the amount of which can readily be calculated. In the case of a cloud of scattered material the angular velocity is not uniform, but increases towards the centre, the rate of increase depending on the importance of the central condensation. In that case the local angular momentum of any given portion of the material is less than it would be if the angular velocity were uniform. The actual angular momentum would have a value corresponding with an angular velocity between $\frac{1}{4}\alpha$ and α, where α is now the angular velocity of rotation of the region in question about the centre of the cloud.

The angular momentum of a portion of the primitive cloud having a mass equal to that of the solar system can therefore be calculated, and it is found that the angular momentum of such a mass of material would be thousands of times greater than the angular momentum of the solar system at the present time. The process of evolution by which the primitive cloud of scattered material has been condensed to form stars, planets and so forth involves therefore the dissipation of local angular momentum, or more precisely the transfer of local angular momentum from the various local systems to the system as a whole.

It will thus be seen that the problem which emerges from our preliminary analysis is exactly the reverse of that which is associated with theories of the collision type. In these theories it is assumed that the primitive material was initially devoid of rotation, or nearly so, and the problem which presents itself is to explain the introduction of the additional angular momentum which is possessed by the planets.

In the present theory, on the other hand, the primitive material is necessarily endowed with an excess of angular momentum and the problem is to discover what has happened to it.

Evolutionary Factors in a Rotating Cloud

A non-rotating mass of material, under the influence of gravitation, takes the form of a sphere; if it is rotating slowly it takes the form of a spheroid, as in the case of the Sun and the planets;

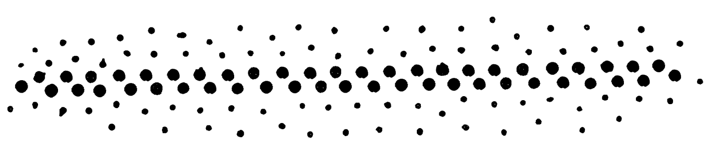

FIG. 1.

if it is rotating rapidly it takes the form of an ellipsoid. A rotating mass of scattered material takes the form of a disk, and it is with structures of this type that we are immediately concerned. The thickness of the disk is proportional to the random velocity of the particles; if the random velocity is negligible the thickness of the disk is very small, as in the case of Saturn's rings, which may be regarded as a typical example of a structure of this type.

The process of evolution in a rotating cloud of scattered material can be divided into three main stages.

In the first stage, in which the particles are more or less uniformly distributed in the form of a disk, the random velocity is reduced by inelastic collisions and the disk grows thinner. In this stage there may be a tendency for the larger particles to separate themselves from the remainder and form a thin central sheet with a gaseous atmosphere on either side of it (fig. 1).

The reduction in the thickness of the disk involves an increase in the local density, and this causes the structure to become unstable and marks the beginning of the second stage. On the first appearance of instability the motion of the particles becomes turbulent; subsequently local eddies are formed, each eddy rotating upon itself and having a higher density than the remainder of the cloud.

The growth of instability is governed by the ratio $\rho'/\bar{\rho}$, where ρ' is the local density and $\bar{\rho}$ the mean density of the system, the latter being defined by the equation $\bar{\rho}=3M/(4\pi a^2)$, where a is the distance from the centre of the system. The critical values of the ratio are:

(i) When $\rho'/\bar{\rho}$ is less than 0·022 the original disk is stable.
(ii) When $\rho'/\bar{\rho}$ is greater than 3, local condensations are stable and assume a separate existence.
(iii) When $\rho'/\bar{\rho}$ is greater than 14·5, a local condensation can take the form of a solid body rotating with uniform angular velocity.

The size and number of the condensations can be estimated, and are found to depend on $(M/m)^2$, where M is the mass of the central condensation and m is the mass of the rotating cloud. If this quantity is large the condensations formed are small and numerous.

Local condensations have been formed, viscous friction between each condensation and its neighbours slows down the rotation, the orbits of the particles contract and the central density of the condensations increases.

The process of evolution now passes into the third stage, in which the starting-point is a rotating cloud containing within itself a number of smaller condensations each somewhat denser than the remainder of the cloud and rotating upon itself.

It has sometimes been argued that these condensations would condense upon themselves and that the size and number of the bodies ultimately formed must be equal to the number of these original condensations, but it is clear that this argument is not valid. There are in fact three things which may happen:

(i) The condensations may separate from one another and may become unstable and break up again into still smaller condensations.
(ii) The condensations may condense upon themselves.
(iii) The original condensations may coalesce, thus forming larger and larger condensations until only one large condensation remains in each particular region.

These various developments may conveniently be discussed in their application to specific cases.

The Formation of Planetary Clouds

In the course of its evolution the solar system has passed through various stages, an early stage which saw the evolution of the Sun and later stages which witnessed the evolution of the planets

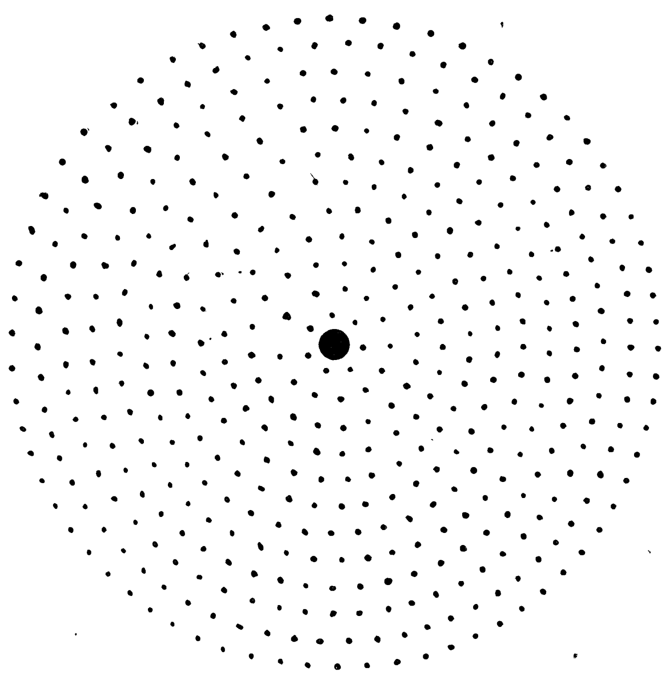

FIG. 2.

and their satellites. For our present purpose it is convenient to postpone consideration of the earlier and more remote problem of the evolution of the Sun, and we start therefore by postulating the Sun in very much its present form, surrounded by a rotating cloud of scattered material extending beyond the present orbits of the planets. This cloud, which would have the form of a disk, is indicated diagrammatically in fig. 2.

The first stage in the evolution of such a cloud, as already explained, is the reduction of the average random velocity by inelastic collisions, so that the disk becomes thinner.

As a result of becoming thinner the rotating cloud became unstable, and a large number of small condensations or eddies were formed within the structure of the cloud itself. Being unable to expand owing to the presence of its neighbours, the rotation of each individual condensation was retarded and it contracted upon itself and became denser. The process would be slow, however, and for a considerable period the continuity of the cloud would remain unbroken. We thus arrive at the picture of a rotating cloud containing within itself a number of local condensations, each condensation rotating on itself and being capable of independent movement (fig. 3).

Being of higher density than the remainder of the cloud, the condensations attracted one another and collisions occurred; since such collisions were essentially inelastic the colliding condensations often coalesced to form a single condensation of larger mass. Again, the motion of the condensations within the cloud was subject to viscous friction; when two condensations approached each other they often failed to separate again even when there was no collision. This process resulted in a continual decrease in the number of condensations and a corresponding increase in their individual mass, so that ultimately only one large condensation remained in each particular

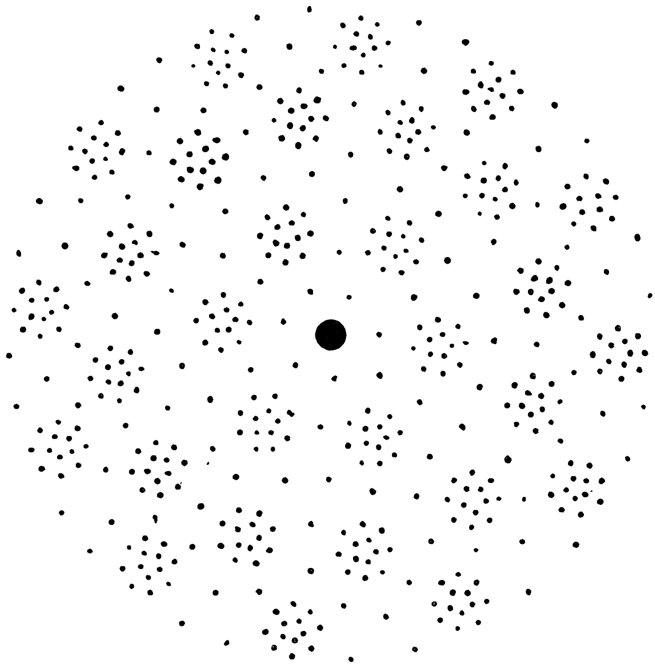

FIG. 3.

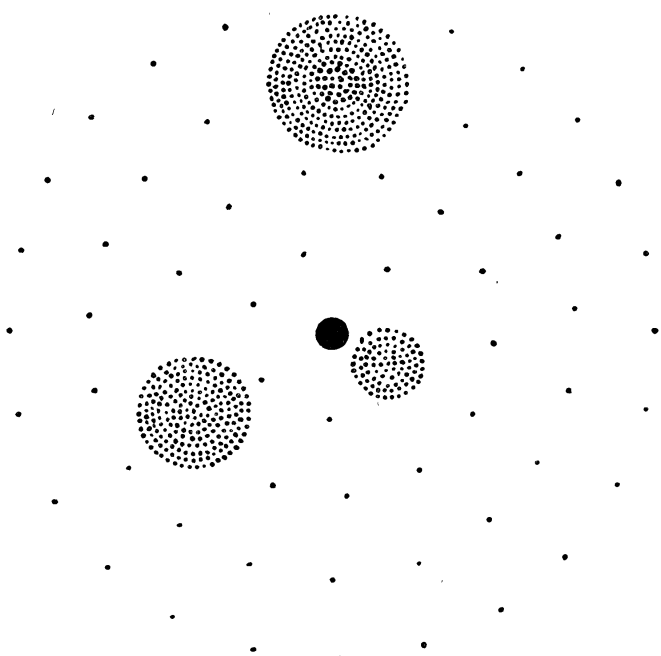

FIG. 4.

region, and the original scattered cloud was replaced by a small number of separate and much denser clouds, each revolving about the Sun and rotating upon itself (fig. 4).

Each of these separate clouds provided the material which ultimately developed into a planet and its satellites.

The Evolution of a Planet

Let us now consider the further history of one of these rotating planetary clouds, let us say the cloud which was ultimately destined to form the planet Jupiter and its satellites. The extreme radius of the cloud is given by the formula

$$r = a(m/3M)^{1/3}$$

where a is the distance from the Sun and m and M are the masses of the cloud and of the Sun respectively. The value of $(m/3M)$ for Jupiter works out at 0·0683 or 1/14·6.

At this stage in our analysis it is convenient to introduce a quantity Q which may be called the opacity.

Let n = the number of particles per cm.^{2} of the area of the disk.
„ b = the radius of a particle.

The proportion of light intercepted by a layer of widely scattered material is πnb^2, and this quantity may be called the opacity and may be denoted by Q.

While we are not actually concerned with the transmission of light, the quantity which we have called the opacity is an important factor in determining various properties of a cloud of small solid particles, and in what follows Q will be used in the sense defined above, irrespective of whether the disk of material under discussion is capable of transmitting light or not. Assuming that b is 0·25 cm. the average value of the opacity for the assumed cloud is 23,000.

Corresponding values of the opacity for other planets vary from 160 in the case of Mars to 2000 in the case of Saturn.

In considering the evolution of a planetary cloud there are three main factors to be taken into account:

(i) Inelastic collisions between the particles. These cause loss of energy and a reduction of the random velocity, so that orbits tend to become more circular.

(ii) Perturbations in the orbits of the particles in their motion about the centre of gravity of the local condensation due to the influence of the Sun. These perturbations tend to make the orbits more eccentric and random velocities are increased. The process involves a loss of energy and a loss of angular momentum.

The combined effect of these two factors is a loss of energy and angular momentum and the orbits contract.

(iii) Viscosity. Since the angular velocity of the rotating cloud is greater near the centre and diminishes as we proceed outwards, there is a transfer of energy and angular momentum in an outward direction owing to viscous friction; that is to say, the inner layers are retarded and the outer layers are accelerated, so that orbits near the centre contract and those near the periphery tend to expand.

If the random velocity of the particles is known, the rate at which energy is gained owing to viscosity and lost owing to inelastic collisions can be calculated. The ratio between the two rates can then be written down and is found to be independent of the random velocity and proportional to Q^2. For the inner parts of the cloud the two effects reinforce one another. For the outer parts of the cloud there is a critical value of Q at which the effect of the inelastic collisions and the effect of viscosity are equal and opposite. This critical value is about 4. For larger values of Q the inelastic collisions are the dominating factor and the cloud contracts.

As we have already seen, the value of Q for all the planets is greatly in excess of this critical value, and the mechanism responsible for the contraction of the cloud of scattered material and for the formation of the planet is therefore clear. The contraction of the planetary clouds was due to the combined effect of inelastic collisions and of the perturbations caused by the Sun.

The Satellites

During the inflow of material which led to the formation of the planet, the opacity of the rotating cloud decreased and the rate of inflow diminished, leaving a residual cloud of much lower opacity which ultimately condensed to form the satellites.

For the reasons already stated the cloud of scattered material surrounding a planet would become unstable and local condensations would make their appearance. In the earlier stages, however, the inflow of material towards the planet would be so rapid that any condensations which were formed would be swept away and would be absorbed by the planet. Subsequently, when the opacity became low enough and the inflow of material was reduced, the condensations persisted and coalesced to form the satellites after the manner already described.

The Asteroids

The region occupied by the asteroids would no doubt have been occupied by another planet had it not been for the influence of Jupiter. The dynamical problem is the same as that already discussed in regard to the evolution of Jupiter from a planetary cloud, except that we are now dealing with a cloud of scattered material rotating about the Sun and the rôles of the Sun and Jupiter are reversed. The perturbations due to Jupiter in the scattered material in this region drove a large proportion of the material inwards towards the Sun; and, not only was the amount of material substantially reduced, but the opacity of the cloud was reduced also, and the condensations formed were smaller and failed to coalesce. The condensations formed simply condensed upon themselves to produce a large number of small planets instead of coalescing to form one large one.

The Comets

It is not to be supposed that the cloud of scattered material which ultimately condensed to form the solar system was bounded by the present orbit of the planet Pluto; it is evident that it must have extended to much greater distances. It must also be supposed that the opacity of the cloud diminished at greater and greater distances from the Sun. Since the formation of a single large planet is only possible when the opacity is not too low, it is evident that the condensations formed in this outer region would be unable to coalesce; they simply retained their individuality and condensed upon themselves. It may be inferred that the outer region of the solar system, beyond the orbits of the planets, is occupied by a very large number of comparatively small bodies.

In many ways these small bodies would resemble the asteroids, but there is this difference: the asteroids have developed sufficient cohesion to adhere together to form solid bodies, whereas the comets have remained what they were from the beginning—astronomical heaps of gravel without any cohesion. The difference is probably due to differences in the temperatures of the regions in which they were formed.

From time to time a member of this swarm of potential comets wanders from its own sphere and appears as an occasional visitor to the inner regions of the solar system.

The Moon

The Moon is too large a body to have been formed in the manner suggested above for the formation of the satellites, and the existence of some other mechanism is indicated.

When a cloud of scattered material is rotating about a binary system, the effect of perturbations is to cause a transfer of angular momentum to the rotating cloud, so that the cloud expands. It is evident that an ellipsoidal star or planet rotating in the centre of the cloud produces a similar result.

In absorbing material from a rotating cloud a planet acquires the angular momentum of the absorbed material. The period of revolution of a particle moving close to the surface of a sphere of unit density is about $4\frac{3}{4}$ hours and is independent of the size of the sphere; for a planet of the density of the Earth the corresponding period would be about 2 hours. These periods of revolution correspond with an endowment of angular momentum which would be impossible for a rotating planet, and it is clear that there must be some mechanism which enables the surplus angular momentum to be dissipated.

The shape of the planet depends on its period of rotation, and, if the dissipation of angular momentum is not sufficiently rapid, the planet may assume the shape of an ellipsoid instead of a spheroid. In that case the inner part of the rotating cloud is pushed outwards by the planet at the same time that the outer part is pushed inwards by the Sun. Such conditions favour the formation of an abnormally large satellite, since material is retained in the rotating cloud which would otherwise be absorbed by the planet.

If the above theory is correct, it appears that the Moon was formed out of the same primitive material as the Earth, so that it has never formed part of the Earth as has sometimes been supposed.

It is not impossible that the formation of other large satellites such as Titan and Triton may be due in part to similar causes.

Planetary Rotations

Since the speeds of rotation of the planets must originally have been considerably greater than they are at present, it is necessary to postulate some mechanism capable of reducing the speed of rotation, and the only known mechanism capable of producing this result is tidal friction.

In the case of the Earth rotation is still being slowed down by ocean tides in certain particular localities, but the magnitude of the effect is insufficient. It must be inferred therefore that there was a period, and a period of considerable duration, during which the Earth remained molten.

We have no precise knowledge of the internal constitution of the other planets, but there are certain known features in the case of the Earth which appear to be significant.

The Earth's crust contains an appreciable amount of radio-active material which is now concentrated within a depth of about 40 miles from the surface. It is highly improbable that these radio-active ingredients were so unequally distributed in the original material, and it may therefore be inferred that the radio-active ingredients were originally distributed much more uniformly throughout the whole mass of the planet.

After a sufficient lapse of time the effect of radio-active material is to raise the temperature of the body in which it is located, and the actual temperature depends on the distribution of the radio-active material and on the insulating properties of the material in which it is embedded. If the radio-active material were placed at the centre of a solid sphere, the temperature would be a maximum; if it were placed on the surface, the temperature would be negligible. In the case of a molten planet surrounded by a thin crust, it may be assumed that the molten interior would be maintained at approximately constant temperature by convection, and that the temperature of this molten interior depends on the thickness of the crust.

It can be shown that the present distribution of radio-active material is consistent with the internal temperature of the Earth. If the radio-active material were equally distributed, on the other hand, the interior of the planet would be molten and the thickness of the crust would be about 200 miles only.

These considerations suggest that the Earth passed through three distinct periods since its formation:

(i) A period of rising temperature which came to an end when the material melted.

(ii) A period of constant temperature during which the interior of the planet was molten and was protected by a thin surface crust. During this period the radio-active material gradually separated from the remainder and became segregated near the surface.

(iii) A period of falling temperature during which the thickness of the crust increased. This period, or at least the latter part of it, can be identified with the geological period of the Earth's history.

It is impossible in the space available to discuss planetary rotations in detail, but the rotations of some of the asteroids are of special interest. It has been observed that some of these bodies are of elongated shape and that their periods of rotation are comparatively short. These features are consistent with the theory that the asteroids have been formed by the condensation of rotating clouds of scattered material, but it is difficult to see how they can be accounted for in any other way.

The Sun

At first sight it might appear that the mechanism which was responsible for the formation of the planets must also have been responsible for the formation of the Sun, but there is an important difference.

The contraction of the rotating planetary clouds was attributed to the perturbations caused by the Sun, and the presence of the Sun was an essential factor in the mechanism of evolution. At the present time the solar system is isolated in space, and, if this explanation is accepted, it must be postulated that the Sun was originally associated with some other star or group of stars, and that this system was afterwards disrupted by the close approach of some other system. This is a possible solution, but there are also other possibilities.

It is clearly possible that the solar system may have been formed from a non-rotating cloud (which formed the Sun) surrounded by a rotating fringe (which formed the planets), and the question arises as to how such a structure could have come into existence.

It may be postulated that the galaxy contained, and may still contain, a number of rotating clouds of stellar mass and of considerable size, that is to say as large or larger than the outer boundaries of the solar system. Collisions between such clouds would not be infrequent. If two such clouds came into collision, the collision would be inelastic, and the clouds would probably amalgamate to form a single system. The angular momentum of the combined system would be the sum of the angular momentum associated with the velocity of approach and the angular momenta of the individual systems. In a certain proportion of cases the resultant angular momentum would be zero or almost zero.

In this connection it may be noted that the rotation of an eddy formed in a rotating cloud is a relic of the original rotation and is normally direct, but the rotation associated with the velocity of approach of two eddies tends to be retrograde. Also, it is observed that the rotations of binary systems are in all possible directions.

Following such a collision as we have assumed, initial random velocities would be high, but they would be reduced by inelastic collisions. Particles with very small angular momenta would gravitate towards the centre and would form a central star. Other particles with larger angular momenta would form a rotating fringe. In due course the system would evolve into a central star surrounded by a rotating cloud such as was postulated in an earlier section when the subsequent evolution of the cloud was discussed.

At the moment it does not seem to be possible to decide between these two alternative origins for the Sun, but further study may perhaps suggest that one of these alternatives is more probable than the other.

The Galaxy

The thickness of the galactic disk is about one-thirtieth of its diameter, and there appears to be no *a priori* reason why it should be so thin; or, to express the matter somewhat differently, there is no *a priori* reason why the random velocities of the stars in the neighbourhood of the Sun should be only one-thirtieth of the velocity of rotation. If it is postulated that the disk was originally thicker and that it was composed of scattered material, it may be supposed that its thickness was reduced by inelastic collisions. Assuming that the thickness of the disk was reduced by one half in 10^9 years, the radius of the particles can be deduced, and is found to be about one-half a millimetre, a result which can be inferred from considerations of an entirely different character.

Owing to the reduction in the thickness of the disk it became unstable, and in due course condensations were formed. With only a small degree of central condensation these condensations were large and comparatively few in number.

As a result of viscosity the condensations contracted upon themselves and the central density of each condensation increased, but the process was very slow. Meanwhile inelastic collisions reduced the random velocity of the particles still further, and the original condensations became unstable and broke up again into smaller condensations.

This process was probably repeated several times. The effect of each successive break-up was to increase the opacity of the rotating clouds, and at the same time the condensations at the centre of the clouds became more pronounced. These developments paved the way for the final condensations which resulted in the formation of the stars and planets.

In the actual formation of the stars two different evolutionary processes appear to have been at work. In the first, which may be called the solitary type, the star was formed in isolation from a non-rotating cloud of material without the intervention of any other body. In the second, which may be called the planetary type, the star was formed from a rotating cloud of material in close association with another star or group of stars, the local angular momentum being transferred, by the mechanism already described, to the angular momentum of the system as a whole.

The general theory which is outlined above receives support from certain observed features of the galaxy. Binary systems are fairly common, and there are groups and clusters which can be regarded as survivals of the larger condensations which were characteristic of the intermediate stages which preceded the formation of the present structure.

Summary and Conclusion

The paper traces in broad outline the course of events which appears to have led to the formation of the stars, planets and other astronomical bodies from a vast cloud of widely scattered material, and it is suggested that the solar system has been evolved as a normal product of this general evolutionary process.

Emphasis is laid on the fact that the redistribution of angular momentum is an essential feature of astronomical evolution, and mechanisms are described which are capable of explaining the transfer of angular momentum from one system to another.

It is not claimed that the suggested theory is final or that details may not need amendment, but it is hoped that it may be accepted as a plausible description of the general character of the evolutionary process.

Solar Activity from 1943 January 9 to May 26: Synodic Rotations Nos. 1195, 1196, 1197, 1198 and 1199

By F. J. Sellers, M.I.Mech.E., F.R.A.S.

Partly with a view to saving space and paper, and partly because, now that the Sun is quietening down, there is less to record, I am trying to condense these summaries and have included five rotations in the present report covering considerably over one-third of the year.

Spot-group frequency has declined since the last report but has not quite reached the same low point as in the third quarter of last year, while prominences and flocculi appear to have been rather more numerous. There have, however, been more observations of prominences at different times of the day and, prominences being often transitory, this might, in some slight measure, partly account for the higher frequency.

Synodic Rotation	Limiting Dates	Spot-groups				Prominences						Flocculi							
												Dark				Bright			
		Observations	Mean Daily Frequency	North	South	Observations	M.D.F.	North	South	East	West	Observations	M.D.F.	North	South	Observations	M.D.F.	North	South
No. 1195	1943 Jan. 9 – Feb. 5	16	1·6	11	14	12	8·5	53	49	61	41	11	9·5	54	50	12	2·6	15	16
1196	Feb. 5 – Mar. 5	18	1·5	23	4	9	7·9	35	36	37	34	8	10·7	40	46	8	2·7	15	7
1197	Mar. 5 – Apr. 1	26	1·7	35	10	16	9·3	69	80	72	77	12	10·7	70	58	12	2·2	21	5
1198	Apr. 1 – Apr. 28	26	1·8	26	20	13	8·7	51	62	56	57	9	11·2	48	53	9	2·9	15	11
1199	Apr. 28 – May 26	22	1·3	24	5	12	9·1	48	61	48	61	3	10·3	11	20	3	3·3	5	5
	Totals	108	1·6	119	53	62	8·8	256	288	274	270	43	10·5	223	227	44	2·6	71	44