STOCKHOLMS OBSERVATORIUMS ANNALER
(ASTRONOMISKA IAKTTAGELSER OCH UNDERSÖKNINGAR Å STOCKHOLMS OBSERVATORIUM)
BAND 14. N:o 5.

ON THE COSMOGONY OF THE SOLAR SYSTEM

II

BY

HANNES ALFVÉN

WITH 12 FIGURES IN THE TEXT

COMMUNICATED OCTOBER 14th 1942 BY C. W. OSEEN AND B. LINDBLAD

STOCKHOLM
ALMQVIST & WIKSELLS BOKTRYCKERI-A.-B.
1943

UPPSALA 1943
ALMQVIST & WIKSELLS BOKTRYCKERI A.-B.

On the Cosmogony of the Solar System

II

by

HANNES ALFVÉN.

With 12 figures in the text.

Communicated October 14th 1942 by C. W. OSEEN and B. LINDBLAD.

In the first part of this paper[1] the general principles of a cosmogony of the solar system were laid down. They were compared with observational data with a result which must be considered as encouraging for further attempts to develop the theory. This will be done in this second part of the paper.

It is clearly understood that it is a very precarious task to develop a cosmogony. The purely scientific part of it is of course to try to find the physical laws which have governed the formation of the planets and satellites. Even if these are found, however, we cannot expect to be able to explain the whole complexity of the planetary system without a rather large number of auxiliary assumptions about the details of the process through which the system was formed. It is very difficult to make these assumptions unarbitrary, and in some respects it seems impossible to do more than find assumptions as simple and probable as possible. Nevertheless it is of so much interest to try to reconstruct the formation, even entering somewhat into details, that an attempt to do so will be made.

A. Formation of planets and satellites.

1. On the recombination of the ions.

In the previous paper[1] some laws governing the condensation were found. Very important is the »two-thirds law», according to which ionised matter — which has

[1] H. ALFVÉN, On the cosmogony of the solar system, Stockholms Observatoriums Annaler, Bd 14, N:o 2, 1942. (Referred to as Part I.)

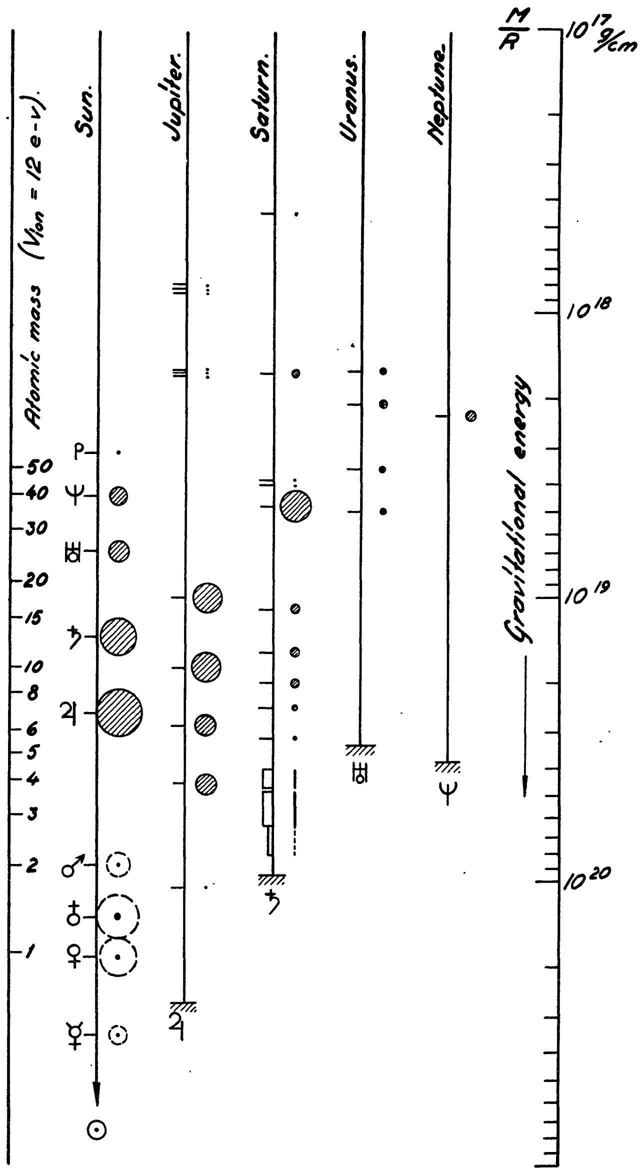

Fig. 1. Gravitational energy of planets and satellites.

moved under the influence of mainly electromagnetic forces — falls down to two-thirds of the distance from the central body when the ions recombine so that the matter becomes non-conducting. This law explains certain details of the structure of the Saturnian rings and also the distribution of the asteroids.

Empirical relations between the ratio of masses (Q) and the ratio of orbital radii (q) of adjacent planets (or satellites) were found (Part I, Fig. 6). The observational values used in Part I were taken from a standard book on astronomy.[1] Since that book was printed new measurements have given more reliable data for some of the satellites. The values which at present seem to be most accurate are compiled in Table 1 and represented in Fig. 2.

In Part I no theoretical explanation was given of the fact that the mass ratio Q and the orbit ratio q are connected as shown in Fig. 2. It is obvious, however, that these relations must be of primary importance in the understanding of the genesis of the planetary system. If the general principles of our cosmogony are valid, it must be possible to derive the relations directly from these principles. We shall now try to do so.

According to Part I the ionized matter captured by the sun's magnetic field can move only along the magnetic lines of force. Sooner or later it will be transported to the equatorial plane. Suppose that in this plane the matter between r and $r + dr$ (r = distance to the sun) amounts to dm. Suppose further that in a certain region we

[1] RUSSEL, DUGAN, and STEWART: Astronomy, Boston 1926.

Table I.

Body	10^{-13} Mean distance	q	Mass Earth = 1	Q	Density Water = 1	Fam.	Gravitational energy $\cdot 10^{-18}$
Planets							
Mercury[1]	0.578	1.87	0.04	20	3.8	II	342
Venus[1]	1.08	1.38	0.81	1.23	4.86	II	183
Earth[1]	1.49		1.00	→ 0.11	5.52	II	133
(Moon)[1]		1.53	0.0123	8.8	3.33	II′	
Mars[1]	2.28	(3.43)	0.108	(2900)	3.96	II′	87
Jupiter[1]	7.78	1.83	317	0.30	1.34	I	25.5
Saturn[1]	14.2	2.04	94.9	0.156	0.71	I	13.8
Uranus[1]	28.7	1.56	14.7	1.17	1.27	I	6.9
Neptune[1]	44.9	1.32	17.2	0.012?	1.58	I	4.41
Pluto[2]	59.1		0.2?		4?	II?	3.09
Martian sat.	10^{-8} Mean dist.		(10^{-6}. Diam.)[3]				
Phobos[1]	9.38	2.51	3.4?	0.15?		I?	0.70
Deimos[1]	23.5		0.51?			I?	0.28
Jovian sat.	10^{-11} M. d. Ref[1]		Jup. = 10^4 Ref[3]		Ref[4]		
V	0.181	2.33				?	105
I Io	0.421	1.59	0.381	0.66	2.66	I	45
II Europa	0.671	1.59	0.248	3.3	2.86	I	28
III Ganymede	1.07	1.76	0.817	0.62	2.16	I	17.8
IV Callisto	1.88		0.509		1.32	I	10.1
Saturnian sat.	10^{-11} M. d.		Saturn = 1 Ref[5]		Ref[5]		
Mimas	0.186	1.28	1 : 14960000	2.26	0.11—0.54	I	31.4
Enceladus	0.238	1.24	1 : 6622000	7.57	0.12—0.62	I	24.5
Tethys	0.295	1.28	1 : 876400	1.62	0.20—0.99	I	19.8
Dione	0.377	1.40	1 : 541300	2.16	0.47—1.97	I	15.4
Rhea	0.527	2.32	1 : 250000	62	0.36—1.55	I.	11.0
Titan	1.22	1.21	1 : 4033	0.0008	3.24	II	4.77
Hyperion	1.48	2.40	1 : 5000000	13.3	1.38—6.24	II	3.92
Iapetus	3.56		1 : 375000		1.03—4.43	II	1.63
Uranian sat.	10^{-11} M. d.		(10^{-8}. Diam.)[3] Ref[1]				
Ariel	0.192	1.39	0.73?	0.47?		II	4.95
Umbriel	0.267	1.64	0.34?	14?		II	3.52
Titania	0.438	1.34	4.9?	0.69?		II	2.16
Oberon	0.586		3.4?			II	1.62

Abnormal satellites (Jupiter VI—XI and Saturn IX) not included. [1] RUSSELL, DUGAN, STEWART, Astronomy. [2] RUSSELL, Solar System and its origin. [3] W. DE SITTER, M. N. 91, p. 734, 1931. [4] Computed out of masses from [3] and diameters from [1]. [5] G. STRUVE, Veröff. Univ. Sternwarte Berlin-Babelsberg VI, Heft 4, 1930. The densities are computed by STRUVE for different reasonable values of the albedo.

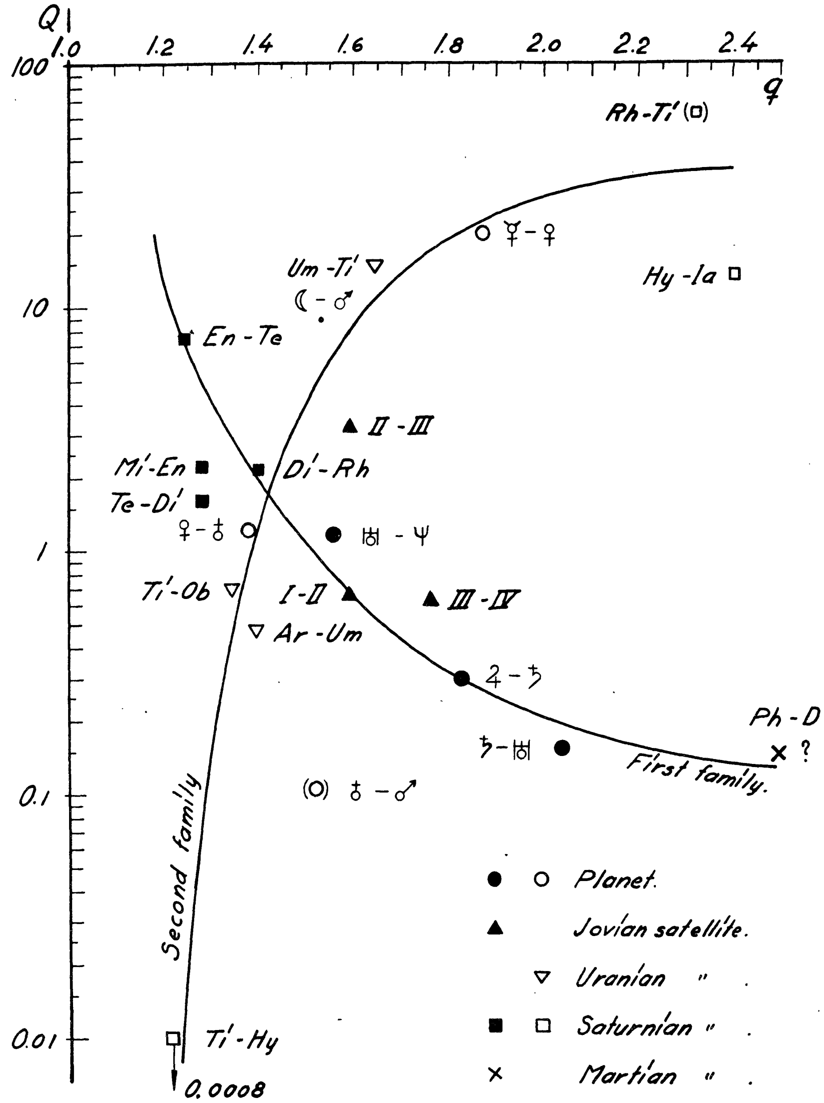

Fig. 2. Empirical connection between masses m_n and orbital radii r_n of planets and satellites.

$$Q = \frac{m_{n+1}}{m_n};\ q = \frac{r_{n+1}}{r_n}.$$

can write

$$\theta = \frac{d\,m}{d\,r} = h\,r^{n-1} \tag{1. 1}$$

where h and n are constants.

In the ionized matter in the equatorial plane ions and electrons will *recombine.* This causes the electromagnetic forces, which have hitherto governed the motion, to vanish. According to Part I the matter recombining at a certain point will start moving in an ellipse, the constants of which were calculated. If recombination takes place at several points, the matter moving in a certain ellipse may collide with matter which has recombined in another point (Fig. 3). The result of such collisions must be an agglomeration of matter and, if we are on the right path, finally the formation of planets.

In order to simplify the calculations we must make some assumptions which are certainly not satisfied very well in reality. Thus we assume:

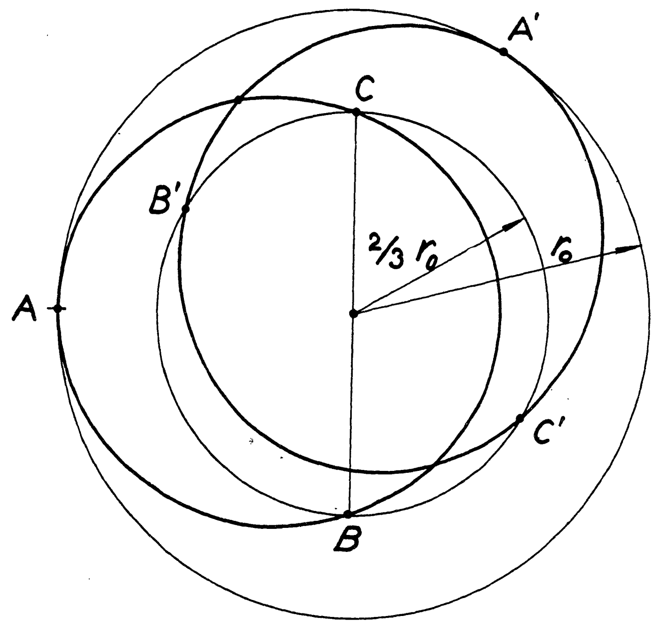

Fig. 3. Ionized matter moves in the circle A A'. Matter recombining in A (or A') starts moving in ellipses A B C (or A' B' C'). Collisions smooth out the ellipses into the circle B C' C B' B.

1. The recombination takes place in such a way that at a certain instant all matter at the distance r recombines and starts moving in ellipses with the eccentricity $e = \frac{1}{3}$. (Compare Part I § 13.)

2. If matter moving in such an ellipse collides with other matter it is captured altogether.

3. The whole process is located at the equatorial plane.

We know that these assumptions cannot be very well satisfied because if so there would be no A-ring in the Saturnian system. The matter constituting the A-ring has come from the region above Mimas, and if our assumptions were correct all this matter would have been captured by this satellite. However, the assumptions will help us to survey the problem, and in § 5 we shall discuss how to modify them in order to approach reality.

2. Recombination starting from outside.

It is impossible to say *a priori* whether the recombination starts from outside or from inside, so we will have to investigate both possibilities. In this section we assume that it starts from outside and proceeds continuously inwards (Fig. 4).

Let us assume that the recombination has proceeded to r_0 and has produced a planet — or a ring coalescing into a planet — which moves (in a circle) at the distance r_0 from the central body. Our problem is to calculate the situation of the next planet.

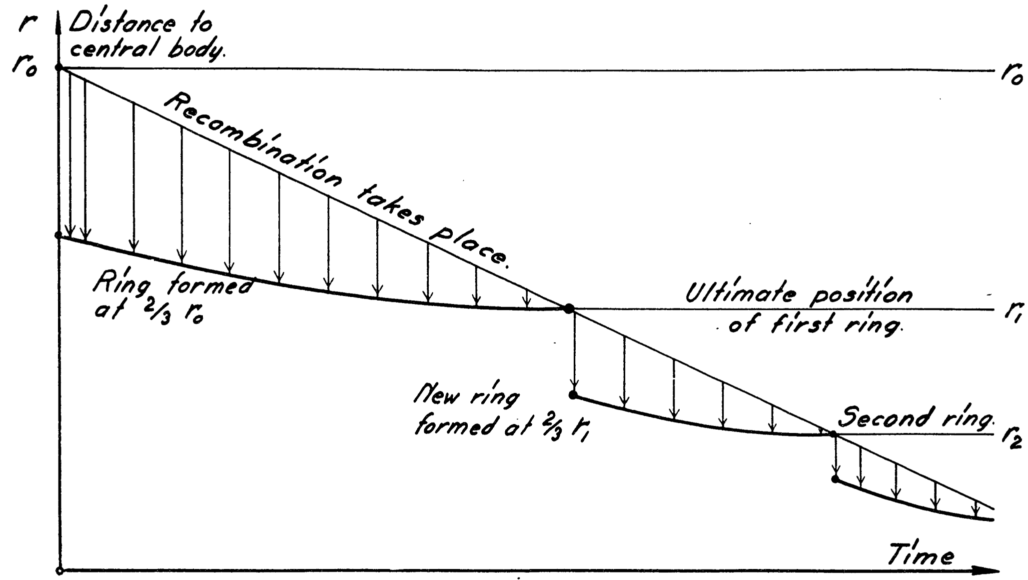

Fig. 4.

Thus we have to study what will occur when the recombination proceeds inwards from r_0. Ionized matter immediately below r_0 recombines and starts moving in ellipses. The recombination takes place symmetrically all along the circle r_0. Through mutual collision the ellipses are flattened to circles with radii equal to $2/3\ r_0$. Thus a *ring* is formed at the distance $2/3\ r_0$. (Fig. 4.)

When recombination proceeds, all neutralized matter originating from the region above this ring (between r_0 and the ring) must pass the ring. Consequently, according to our assumptions, it is captured by the ring. In this way the mass of the ring increases, but at the same time its relative angular momentum (per unit mass) decreases, because the new matter possesses a smaller angular momentum. Thus the radius of the ring decreases continuously until the recombination has reached the ring itself (see Fig. 4). At this moment all matter above r_1 (final radius of the ring) has recombined and the ring has taken up the matter which was originally situated between r_0 and r_1. Later, when the matter below r_1 recombines, a new ring is formed at $2/3\ r_1$ and exactly the same process is repeated, resulting in a new ring at r_2.

The ring at the distance r_1 will coalesce into a planet (through some unspecified process). Its mass amounts to

$$m_1 = \int_{r_1}^{r_0} \theta\, dr = \frac{h}{n}(r_0^n - r_1^n) \tag{2. 1}$$

according to (1. 1). The orbital radius r_1 of the new planet is given by the condition that the angular momentum C must equal the angular momentum of all matter originally situated between r_1 and r_0. Thus we find from (Part I: 13. 1), putting $\triangle = 0$:

$$C_1 = m_1 r_1^2 \omega_1 = \sqrt{\frac{2}{3} k M_\odot} \int_{r_1}^{r_0} \sqrt{r}\, dm \tag{2. 2}$$

For the planet we have

$$\omega_1 = \sqrt{k M_\odot}\, r_1^{-3/2}.$$

Thus we obtain

$$m_1 \sqrt{r_1} = \sqrt{\frac{2}{3}} \int_{r_1}^{r_0} \sqrt{r}\, dm = \sqrt{\frac{2}{3}} \int_{r_1}^{r_0} \theta \sqrt{r}\, dr$$

or

$$m_1 \sqrt{r_1} = \sqrt{\frac{2}{3}} \frac{h}{n + \frac{1}{2}} \left(r_0^{n+\frac{1}{2}} - r_1^{n+\frac{1}{2}}\right). \tag{2. 3}$$

As long as the condition (1. 1) is satisfied the consecutive planets will be situated at regular intervals so that the ratio

$$q = \frac{r_0}{r_1} = \frac{r_1}{r_2} (> 1) \tag{2. 4}$$

between their orbital radii is constant.

The ratio Q between their masses is

$$Q = \frac{m_0}{m_1} = \frac{m_1}{m_2} = q^n \tag{2. 5}$$

according to (2. 1).

Combining (2. 1), (2. 3), (2. 4) and (2. 5) we obtain a relation between q and Q.

$$q^n - 1 = \sqrt{\frac{2}{3}}\,\frac{2n}{2n+1}\left(q^{n+\frac{1}{2}} - 1\right)$$

or

$$\sqrt{\frac{2}{3}}\left(1 + \frac{\log q}{2 \log Q}\right) = \frac{Q\sqrt{q} - 1}{Q - 1}. \tag{2.6}$$

3. Recombination starting from inside.

The other possibility we have to consider is that recombination and condensation start from inside and proceed outwards. (Fig. 5.)

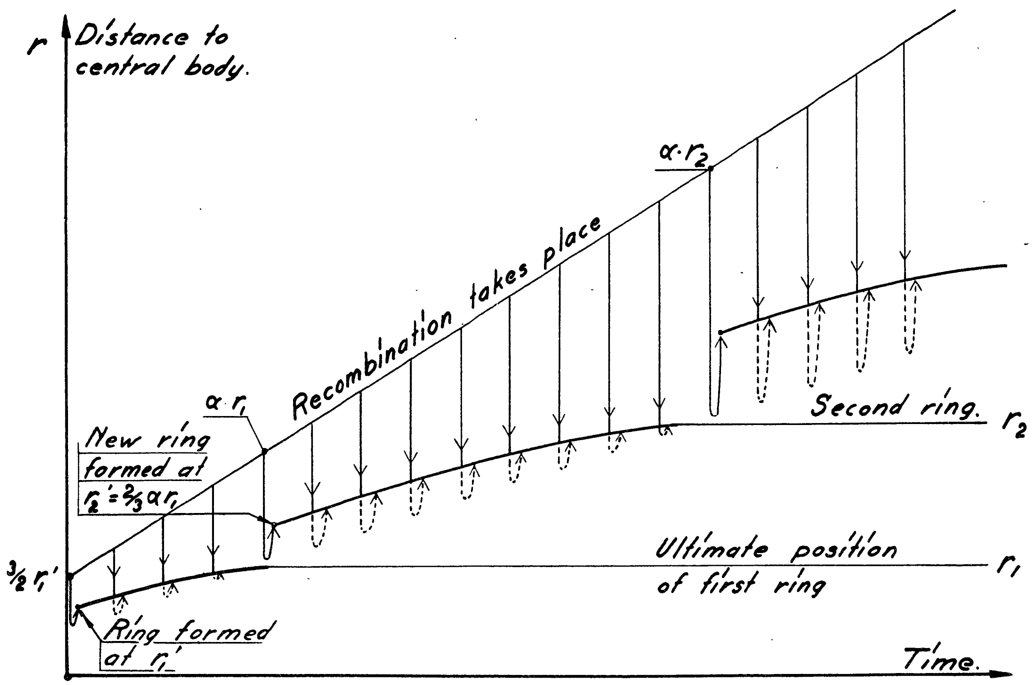

Fig. 5.

Suppose that at a certain instant the recombination has reached a distance which we call $\frac{3}{2}\, r_1'$ from the central body. Matter recombining in that region will, sooner or later, form a circular ring with the radius r_1'. Recombination now proceeds to $r > \frac{3}{2}\, r_1'$. When matter at r recombines it moves at first in ellipses with the eccentricity $e = \frac{1}{3}$. This means that the aphelion is situated at r and the perihelion at $\frac{1}{\alpha}\, r$, where

$$\alpha = 2. \tag{3.1}$$

Thus as long as $r < \alpha r_1'$ the path of the neutralized matter will cut a ring with the radius r_1'. According to our assumptions all this matter is captured by the ring, of which the mass as well as the relative angular momentum increases. This means that its radius increases from r_1' to, let us say, r_1. The process goes on until recombination has reached

$$r = \alpha r_1. \tag{3.2}$$

Matter recombining above αr_1 does not hit the ring r_1, so it will sooner or later form a new ring at $r_2' = \frac{2}{3} \alpha r_1$. This ring will be subject to exactly the same process again until recombination has reached

$$r = \alpha r_2. \tag{3.3}$$

In analogy with § 2 we obtain

$$m_2 = \int_{\alpha r_1}^{\alpha r_2} dm = \int_{\alpha r_1}^{\alpha r_2} \theta\, dr \tag{3.4}$$

and

$$C_2 = \sqrt{\frac{2}{3} k M_\odot} \int_{\alpha r_1}^{\alpha r_2} \sqrt{r}\, \theta\, dr. \tag{3.5}$$

This gives

$$\sqrt{r_2} \int_{\alpha r_1}^{\alpha r_2} \theta\, dr = \sqrt{\frac{2}{3}} \int_{\alpha r_1}^{\alpha r_2} \theta \sqrt{r}\, dr. \tag{3.6}$$

Introducing (2.4) and (2.5) we find finally

$$\sqrt{\frac{3}{2\alpha}} \left(1 + \frac{\log q}{2 \log Q} \right) = \frac{Q - \frac{1}{\sqrt{q}}}{Q - 1} \tag{3.7}$$

with

$$\alpha = 2. \tag{3.8}$$

4. Comparison with observation.

Those dots in Fig. 2 which according to I belong to the first family, are plotted in Fig. 6. In the same figure a curve A representing equation (2.6) is drawn. It is evident that there is a qualitative agreement between theory and observation, the Q-values decreasing with increasing q-values. Certainly the agreement is not quantitative, but this could hardly be expected because of the very simplified assumptions in the theory.

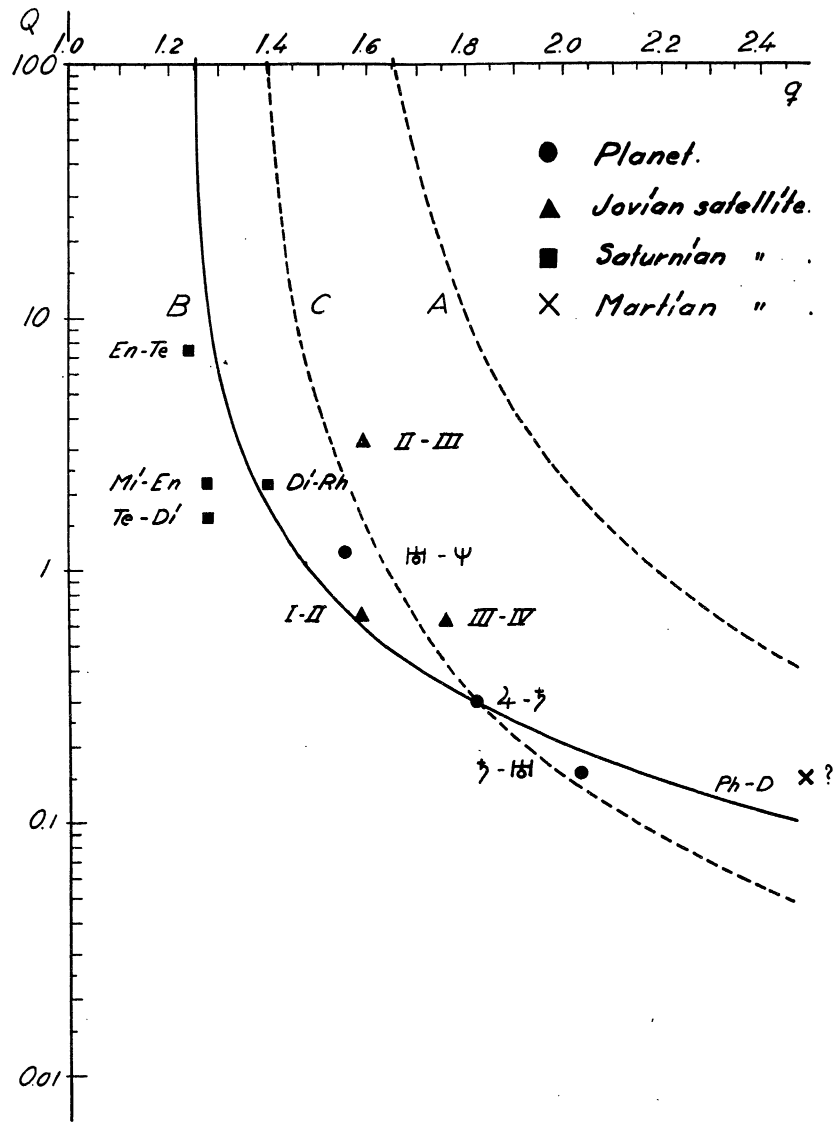

Fig. 6. *First family.*
Theoretical curves: A represents (2.6).
B » (6.3).
C » (6.7).

Thus it seems possible that the *planets and satellites of the first family* have been formed through a *condensation starting from outside* and proceeding inwards.

The second family is represented in Fig. 7. The Q-values increase with increasing q. It is evident that these bodies cannot have been formed by the same sort of process as the first family. However, a condensation starting from inside as analysed in § 3 gives a curve of this character, as shown by the curve A which represents the equation (3.7). Thus there is some indication that the bodies of *the second family* are formed through a *condensation starting from inside* and proceeding outwards.

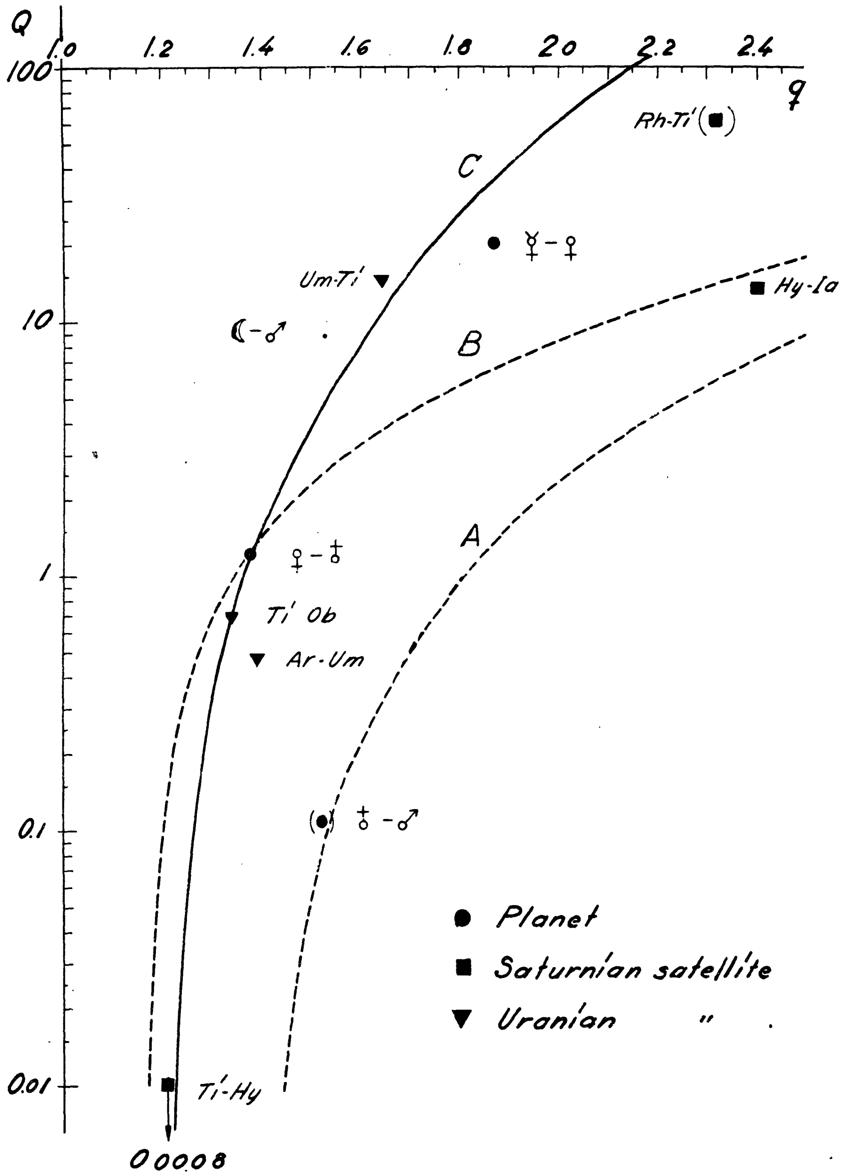

Fig. 7. *Second family.*
Theoretical curves: A represents (3.7) with $\alpha = 2$
C » » » $\alpha = 1.75$.

In this case also the agreement between observation and theory is not quantitative. However, it is somewhat satisfactory that the relative position between the observational dots and the theoretical curve is about the same in both cases. This indicates that some modification of the theory may give better agreement in both cases at the same time.

5. Possible modifications of the theory.

In seeking possible modifications of the theory it would be best to study the Saturnian ring system. As has been pointed out in § 1 the ring system could not be such as it is if we supposed that the recombination had taken place in the equatorial plane only. For example, when the A-ring has just been formed, matter inside Mimas but outside the A-ring recombines and falls down forming the B-ring. If the motion of the neutral particles be confined to the equatorial plane, this matter must pass through the A-ring and certainly collide with the particles of this ring in such a way that the regular structure of the rings will vanish.

On the other hand, if recombination takes place also at some distance from the equatorial plane, the neutral particles will move in ellipses, the planes of which make

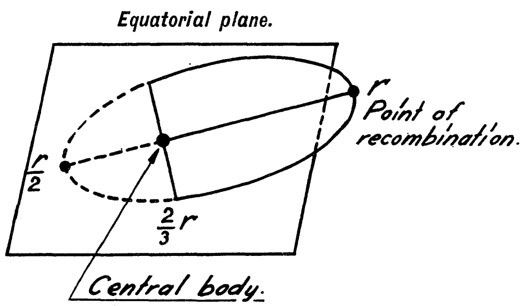

Fig. 8.

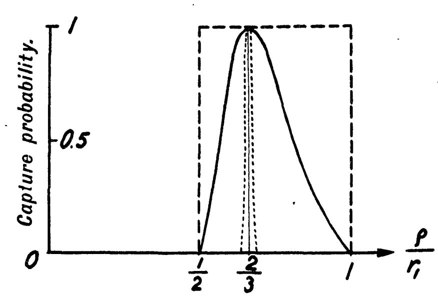

Fig. 9. Capture probability.
- - - according to assumptions in § 3 und § 4.
—— for formation of planets.
.... » » » the Saturnian rings.

a small angle with the equatorial plane. The ellipses of particles formed at the distance r from the central body intersect the equatorial plane at two points at the distance $\frac{2}{3}r$ (See Fig. 8). Consequently, particles formed at the distance r from the central body but at different longitudes and different distances from the equatorial plane will all meet in the equatorial plane on the circle with radius $\frac{2}{3}r$. In this way the formation of a ring at $\frac{2}{3}r$ need not be disturbed by matter between r and $\frac{2}{3}r$ if only this matter forms a flat, very thin ring in the equatorial plane, such as the Saturnian rings.

The above considerations make it evident that we must discard our simplifying assumption that the recombination and condensation take place exactly in the equatorial plane. Thus, matter recombining at r_1 need not be captured altogether by a planet (or a ring coalescing into a planet) which is already present somewhere between r_1 and $\frac{1}{2}r_1$

(= aphelion and perihelion of the ellipse), because it does not move in the same plane. Only if the ring (or planet) is situated at $\varrho = \frac{2}{3} r_1$ will it capture all the matter neutralized at r_1 because all of it must pass the circle $\frac{2}{3} r_1$. The capture probability must decrease if the ring is situated inside as well as outside $\frac{2}{3} r_1$, and if $\varrho = r_1$ or $\varrho = \frac{1}{2} r_1$ it must be zero.

How rapidly the capture probability drops on both sides of $\frac{2}{3} r_1$ depends upon the constitution of the ring already present. If it is flat and very thin as the Saturnian rings, the probability will decrease very rapidly (See Fig. 9). In this case the process leads to the formation of rings of the Saturnian or asteroid type. The formation of big planets and satellites must be intermediate between this and the processes discussed in §§ 3 and 4. Thus we should expect the capture probability to fall approximately as indicated by the full curve in Fig. 9. Such a curve is obtained if the capture is due to a ring which is not very flat.

6. **Modified theory of the condensation, recombination starting from outside.**

We shall now study how this affects the relations between q and Q. In Fig. 10 a the formation of planets and satellites according to § 3 is shown. The condensation starts from outside. A body which is situated at r_2 (for example) is built up of all matter originally situated between r_1 and r_2. This implies the assumption that the capture probability of the ring equals 1 (upper curve in Fig. 9).

If the capture probability is smaller than 1, only a part of the matter between r_1 and r_2 will be captured by the ring ultimately situated at r_2. Part of it will be left to form the next ring (at r_3) and perhaps a small fraction will even take part in the formation of the ring at r_4. See Fig. 10 b.

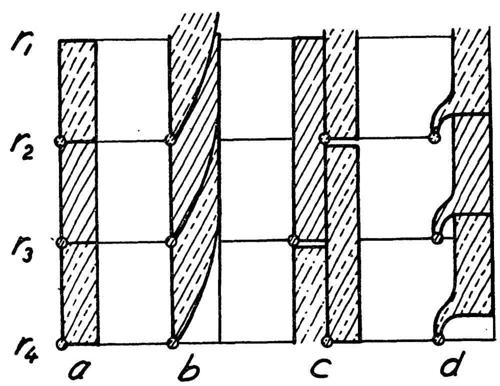

Fig. 10.

The question now arises how we might account for this in our theory without too difficult calculations. There seem to be two rather simple modes of approximation.

The first of these is shown in Fig. 10 c. It is assumed that a ring at r_3 is formed of *half* of all the matter between r_1 and r_3. In the same way the ring at r_4 is formed of half of the matter between r_2 and r_4, and so on. A comparison between Fig. 10 c and b shows the relation between our approximation and what is likely to be the actual process.

It is very easy to introduce this assumption in the theory. Half of all the matter taking part in the process forms the rings r_1, r_3, r_5, ... at distances which are the same as in the original theory. Thus we have

$$q = \frac{r_1}{r_3} = \frac{r_3}{r_5}.$$

The other half of the mass forms rings r_2, r_4, ... intermediate between them.

Thus, if we put

$$q' = \frac{r_1}{r_2} = \frac{r_2}{r_3} = \frac{r_3}{r_4} = \frac{r_4}{r_5} \cdots \tag{6. 1}$$

we obtain

$$q'^2 = q. \tag{6. 2}$$

Thus we must replace q in (2. 6) by q'^2. Similarly way we must replace Q by Q'^2. Omitting the dashes we obtain the equation

$$\sqrt{\frac{2}{3}}\left(1 + \frac{\log q}{2 \log Q}\right) = \frac{Q^2 q - 1}{Q^2 - 1}. \tag{6. 3}$$

There is also a second simple way to modify the theory. For the condensation from outside the capture probability between $\varrho/r_1 = 2/3$ and $= 1$ is of importance. If we put the probability $= 1$ for $\varrho/r_1 < \frac{1}{\beta}$ and $= 0$ for $\varrho/r_0 > \frac{1}{\beta}$ a ring at r_3 (for example) is formed of matter originally situated between βr_3 and βr_2. For the parameter β we have

$$1 < \beta < \frac{3}{2}. \tag{6. 4}$$

The meaning of this assumption is evident from Fig. 10 d. Thus we must replace (2. 1) and (2. 2) by

$$m_1 = \int_{\beta r_1}^{\beta r_0} h\, r^{n-1}\, dr \tag{6. 5}$$

and

$$C_1 = \sqrt{\frac{2}{3} k M_\odot} \int_{\beta r_1}^{\beta r_0} \sqrt{r}\, dm \tag{6. 6}$$

which gives

$$\sqrt{\frac{3}{2\beta}}\left(1 + \frac{\log q}{2 \log Q}\right) = \frac{Q\sqrt{q} - 1}{Q - 1} \tag{6. 7}$$

instead of (2. 6).

The curves representing (6. 3) and (6. 7) are drawn in Fig. 6. In (6. 7) β is tentatively put equal to 1.16. Especially the curve B agrees rather well with the observational data.

7. Modified theory of the condensation, recombination starting from inside.

For the condensation starting from inside the capture probability between $\varrho/r_1 = \frac{1}{2}$ and $= \frac{2}{3}$ is of importance. If we put the probability $= 0$ for $\varrho/r_1 < \frac{1}{\alpha}$ and $= 1$ for $\varrho/r_1 > \frac{1}{\alpha}$, a ring already existing at r will capture all matter recombining inside αr. Thus the formula (3. 7) is still valid if we only replace (3. 8) by the condition $\frac{3}{2} < \alpha < 2$.

In order to give the best agreement with the observational data the parameter α is put equal to 1.75. This curve is drawn in Fig. 7. Most of the observational dots are situated rather close to the curve.

We could also modify the equation (3. 7) (with $\alpha = 2$) in the same way as in § 6, so that we replace q by q^2 and Q by Q^2. This gives the curve B in Fig. 4. The physical basis of such a change, however, seems to be weak.

8. Discussion.

The agreement between the modified theory and observations is of course not decisive because the derivation of the theoretical formulae was not very stringent. Nevertheless it gives rather strong indications that the bodies of the planetary system have been formed in the way which we have supposed.

On the one hand it is very satisfactory that we can explain *both* the Q—q-curves (of first and second family) as results of the same process, the only difference being that in one case it has started from outside and in the other case from inside. Moreover, the process is the same as that responsible for the formation of the Saturnian and asteroid rings.

On the other hand it is necessary to try to discover *why* the process has started once from outside and once from inside.

The chemical composition of the gas cloud forming the bodies of the first family is no doubt different from that of the dust cloud forming the second family. The gas cloud must have contained those elements now present in the giant planets. Most abundant are probably H, O, N, C, and their chemical compounds. Most of these are substances with low boiling points.

The chemical composition of the dust cloud must have been the same as that of our Earth, so that Fe, O and Si are likely to have predominated, the oxygen mainly in chemical combination with silicon. The boiling points of these substances are very high.

In the process of condensation outlined by LINDBLAD[1] a small dust particle increases in size because of the difference in temperature between the particle and the surrounding gas. The process is favoured by a high temperature of the gas. On the other hand the temperature of the particle, which is about the same as the radiation temperature, ought to be low so that the particle does not volatilize, but for a substance with a high boiling point it need not be very low. Thus, a small particle of iron (or some other of the substances most abundant in the dust cloud) will increase more rapidly the higher is the temperature of the surrounding gas. As it is reasonable that when other factors make a recombination possible, the temperature decreases in the outward direction, the condensation is likely to start from the neighbourhood of the central body, so that it proceeds from inside outwards. This is what we have found for the second family.

The same process is not possible for the gas cloud, because its constituents have very low boiling points. A small particle cannot increase its size unless its temperature is so low that it does not volatilize appreciably. Thus we should expect a low temperature to favour the condensation in this case, quite contrary to the conditions in the dust cloud. As the temperature is lowest in the outer regions, this may be the explanation why the condensation starts from outside in the gas cloud.

B. Axial rotation and density.

9. The axial rotation of the planets.

The condensation of the matter into planets will give a certain rotation to these planets. A complete theory of the condensation ought to give not only more satisfactory relations between Q and q than we have found in the preceding sections but also numerical values of the axial rotation of the planets. A complete theory, however, meets with very great mathematical difficulties and we shall confine ourselves to discussing the general lines.

[1] B. LINDBLAD, Nature 135, p. 133, 1935.

Suppose that in the sun's equatorial plane a nucleus M_1 growing to a planet is situated at the point (r_1, α_1). See Fig. 11. The equations of motion of a small particle at (r_2, α_2) are

$$\frac{d^2 r_2}{d t^2} - r_2 \left(\frac{d \alpha_2}{d t}\right)^2 = -k \left(\frac{M_0}{r_2^2} + \frac{M_1}{\varrho^2} \cos \beta\right) \tag{9.1}$$

$$r_2 \frac{d^2 \alpha_2}{d t^2} + 2 \frac{d \alpha_2}{d t} \frac{d r_2}{d t} = -k \frac{M_1}{\varrho^2} \sin \beta \tag{9.2}$$

where k is the gravitational constant, M_0 the sun's mass, ϱ the distance to M_1, and β the angle shown in Fig 11.

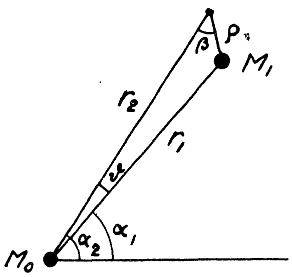

Fig. 11.

Suppose that M_1 moves in a circle around the sun with the constant angular velocity

$$\frac{d \alpha_1}{d t} = \omega_1 = \sqrt{\frac{k M_0}{r_1^3}}. \tag{9.3}$$

We put

$$\frac{d \alpha_2}{d t} = \omega_1 + \frac{d \vartheta}{d t} \tag{9.4}$$

and

$$r_2 = r_1 + r. \tag{9.5}$$

Further we suppose that

$$\frac{d \vartheta}{d t} \ll \omega_1 \tag{9.6}$$

and

$$r \ll r_1; \quad \vartheta \ll 1. \tag{9.7}$$

This gives approximately from (9.1) with the help of (9.3)

$$\frac{d^2 r}{d t^2} - 2 \omega_1 r_1 \frac{d \vartheta}{d t} = r \omega_1^2 - \frac{k M_0}{r_1^2}\left(1 - 2 \frac{r}{r_1}\right) - \frac{k M_1}{\varrho^2} \cos \beta$$

$$= k \left[\frac{M_0}{r_1^2} \cdot 3 \frac{r}{r_1} - \frac{M_1}{\varrho^2} \cos \beta\right]$$

or, as $\cos \beta = \frac{r}{\varrho}$

$$\frac{d^2 r}{d t^2} - 2 \omega_1 r_1 \frac{d \vartheta}{d t} = -k \frac{M_1}{\varrho^2} \cos \beta \left[1 - 3 \frac{M_0 \varrho^3}{M_1 r_1^3}\right]. \tag{9.8}$$

In the same way (9.2) gives

$$r_1 \frac{d^2 \vartheta}{d t^2} + 2\, \omega_1 \frac{d r}{d t} = - k \frac{M_1}{\varrho^2} \sin \beta . \tag{9.9}$$

Let us now introduce $\frac{1}{\omega_1}$ as the unit of time and

$$l = r_1 \sqrt[3]{\frac{M_1}{M_0}} \; (= 1) \tag{9.10}$$

as the unit of length. This means that we put

$$\left.\begin{aligned} r_1 &= r'_1\, l \\ r &= r'\, l \\ \varrho &= \varrho'\, l \\ t &= \frac{1}{\omega_1} t' \end{aligned}\right\} \tag{9.11}$$

As

$$\frac{k\, M_1}{l^3\, \omega_1^2} = 1$$

we obtain from (9.8) and (9.9)

$$\frac{d^2 r'}{d t'^2} - 2\, r'_1 \frac{d \vartheta}{d t'} = - \frac{\cos \beta}{\varrho'^2} (1 - 3\, \varrho'^3) \tag{9.12}$$

$$r'_1 \frac{d^2 \vartheta}{d t'^2} + 2 \frac{d r'_1}{d t'} = - \frac{\sin \beta}{\varrho'^2} . \tag{9.13}$$

A nucleus M_1 can grow to a planet through capturing particles in its environment. If the time is reckoned with $\frac{1}{\omega_1}$ as unit and the distances with l as unit, *the capture process must be exactly the same for all planets*, because (9.12) and (9.13) are the same for all of them.

Consequently, if all the condensations lead to planets having radii equal to R'_0 (reckoned with l as unit) all of them must revolve with the same period τ'_0 $\left(\text{reckoned with } \frac{1}{\omega_1} \text{ as unit}\right)$. If such a planet contracts uniformly so that its radius decreases from R'_0 to R' its period must decrease to

$$\tau' = \tau_0 \left(\frac{R'}{R'_0}\right)^2 \tag{9.14}$$

because the angular momentum must be conserved.

If the radius of the planet is R (expressed in cm so that $R = R' \cdot l$) it revolves with a period τ (in seconds) which according to (9. 14), (9. 11) and (9. 10) is

$$\tau = \frac{\tau'}{\omega_1} = \frac{\tau'_0}{R'^2_0} \frac{R^2}{\omega_1 r_1^2} \left(\frac{M_0}{M_1}\right)^{2/3}. \tag{9. 15}$$

If the planet has the uniform density γ, we have $M_1 = \frac{4}{3}\pi\gamma R^3$. Introducing (9. 3) we obtain

$$\tau = k \frac{1}{\sqrt{r_1}} \frac{1}{(\gamma)^{2/3}} \tag{9. 16}$$

where k is a constant, because τ'_0 and R'_0 are supposed to be constant.

Thus we should expect *the periods of axial rotation of the planets to be proportional to* $r_1^{-1/2}$ (r_1 = orbital radius) *and to* $\gamma^{-2/3}$ (γ = density).

The value of τ given by (9. 16) is the period a planet should have immediately after the condensation under the assumption that its density as well as its rotation are uniform.

Thus in order to obtain the actual period we ought to correct τ for three reasons:

1. Since its formation the rotation of a planet has been braked, probably in the greater part by tidal friction.

2. If the density is not uniform, the period is the shorter the more the mass is concentrated towards the centre.

3. We cannot be certain that the nucleus of a giant planet rotates with the same velocity as the surface which we observe.

Keeping these facts in mind we shall now compare the theory with observations. In Table 2 A is proportional to the theoretical period. It is remarkable that the values of A are almost constant. In fact A varies only between 0.41 and 2.03, so we may say that *all the planets ought to have about the same period* of axial rotation.

Table 2.

	r_1	γ	$A = r_1^{-1/2}\gamma^{-2/3}$	$\tau_{obs.}$ hours	$\frac{\tau_{obs.}}{A}$
Mercury	0.39	0.70	2.03	2112	1040
Venus	0.72	0.88	1.28	720?	560?
Earth	1.00	1.00	1.00	23.9	24
Mars	1.52	0.72	1.01	24.6	24
Jupiter	5.20	0.24	1.14	9.9	9
Saturn	9.54	0.13	1.26	10.3	8
Uranus	19.19	0.23	0.61	10.7	18
Neptune	30.07	0.29	0.41	15.8	39
Pluto	39.51	0.72?	0.20?		

According to observations, for all satellites and for Mercury the periods of axial rotation agree with the siderial periods. This is obviously a result of the tides, so these periods are of no interest for our comparison. The period of Venus seems to differ somewhat from the siderial period, but even in this case the effect of the solar tide has obviously been very large. For all other planets the periods of axial rotation are almost the same, indeed they vary only between 9.9^h and 24.6^h.

If no corrections were necessary, the ratio τ/A would be constant. The very high values of τ/A for Mercury and Venus are obviously due to the sun's tidal action, which probably also makes the values of the Earth and of Mars too high. The Earth is also braked by the Moon's tides. Neptune has a big retrograde satellite close to its surface, the braking action of which may explain its high value of τ/A. The rotations of Jupiter, Saturn and Uranus are certainly not slowed down by tidal friction to any considerable extent.

The low values for Jupiter and Saturn may be due to the high degree of central mass concentration which probably exists in these giant planets.

On the whole, even if we cannot say that observations directly verify our theoretical results, they certainly do not contradict them. If we supposed the »correct» value of τ/A to be 15 or 20 we could very well explain the lower values as due to central mass concentration and the higher values as due to tidal friction.

That the sense of rotation must be direct is seen from (9. 12) and (9. 13). If $\sin\beta = 0$ and $\varrho' = +\sqrt[3]{\frac{1}{3}}$ or $\varrho' = -\sqrt[3]{\frac{1}{3}}$ a particle can rotate around the sun in a position which is fixed in relation to M_1 in the rotating coordinate system. If the particle is displaced a little from the outer of these two points, $\frac{d\vartheta}{dt'}$ will have the same sign as $(1 - 3\varrho'^2)$ because the first term in (9. 12) can be neglected. Thus it will move in the retrograde direction in relation to M_1, if $|\varrho'| > \sqrt[3]{\frac{1}{3}}$, but in the direct sense if $|\varrho'| < \sqrt[3]{\frac{1}{3}}$. The same result is obtained for the point $\varrho' = -\sqrt[3]{\frac{1}{3}}$. As the condensation must go on in the region close to the planet, direct rotation is obtained.

Why the axes of the planets are not exactly perpendicular to the orbital plane — one of them has tipped even a little more than a right angle — cannot be accounted for by the theory in its present state.

10. The density of the planets and satellites.

The density of a body is a function of its chemical composition and its physical state. The chemical composition depends mainly upon the family to which the body belongs. If we classify the bodies in two families according to the curves to which their q—Q-values belong, we find that *all the bodies of the first family have lower densities than those of the second family.*

Among the planets the highest density in the first family is 1.58 (Neptune) whereas the lowest density in the second family is 3.8 (Mercury) or rather 3.33 (Moon, which we must count as a planet). Pluto must probably be counted in the second family because the q—Q-dot of Neptune—Pluto seems to fall not too far from the second family curve. Its density is probably rather high (= 4?).

Of the three q—Q-dots of the four Gallileian satellites of Jupiter two fall close to the first family curve, but one (of the second and third satellites) is intermediate between the two curves. As obviously all the satellites have the same origin, they must be counted in the first family. Their densities vary between 1.32 and 2.86. (Compare § 12.)

The Saturnian satellite Titan has the density 3.24. The q—Q-dot of Titan—Hyperion belongs no doubt to the second family curve. The dot Rhea-Titan also lies close to this curve although this may be fortuitous, because it is dubious whether there is any genetical connection between them. In any case Titan belongs to the second family.

Of no other body is the density known with accuracy.

Thus all the bodies of the first family have densities below 2.86 (varying from 0.71 to 2.86) whereas the bodies of the second family have densities exceeding 3.24 (varying between 3.24 and 5.52).

G. STRUVE[1] has given the upper and lower limits to the densities of the Saturnian satellites Mimas—Rhea and Hyperion—Iapetus. Of these the group Mimas—Rhea belongs no doubt to the first family. This is shown not only by the situation of their q—Q-dots which are closer to the first family curve than to the second family curve, but also by their genetical connection with the ring system which certainly has been built up from outside inwards. The upper limits to their densities as given by STRUVE in no case exceed 1.97, so that the general rule is amply confirmed.

For Hyperion and Iapetus, both certainly of the second family, the limits are 1.38—6.24 and 1.03—4.43. These values neither confirm nor contradict the previous results.

In Fig. 12 the density is plotted as a function of the gravitational energy of the bodies. For the Saturnian satellites (safe Titan) the STRUVE limits of their densities are

[1] G. STRUVE, Veröff. Univ. Sternwarte Berlin—Babelsberg, VI, Heft 4, 1930.

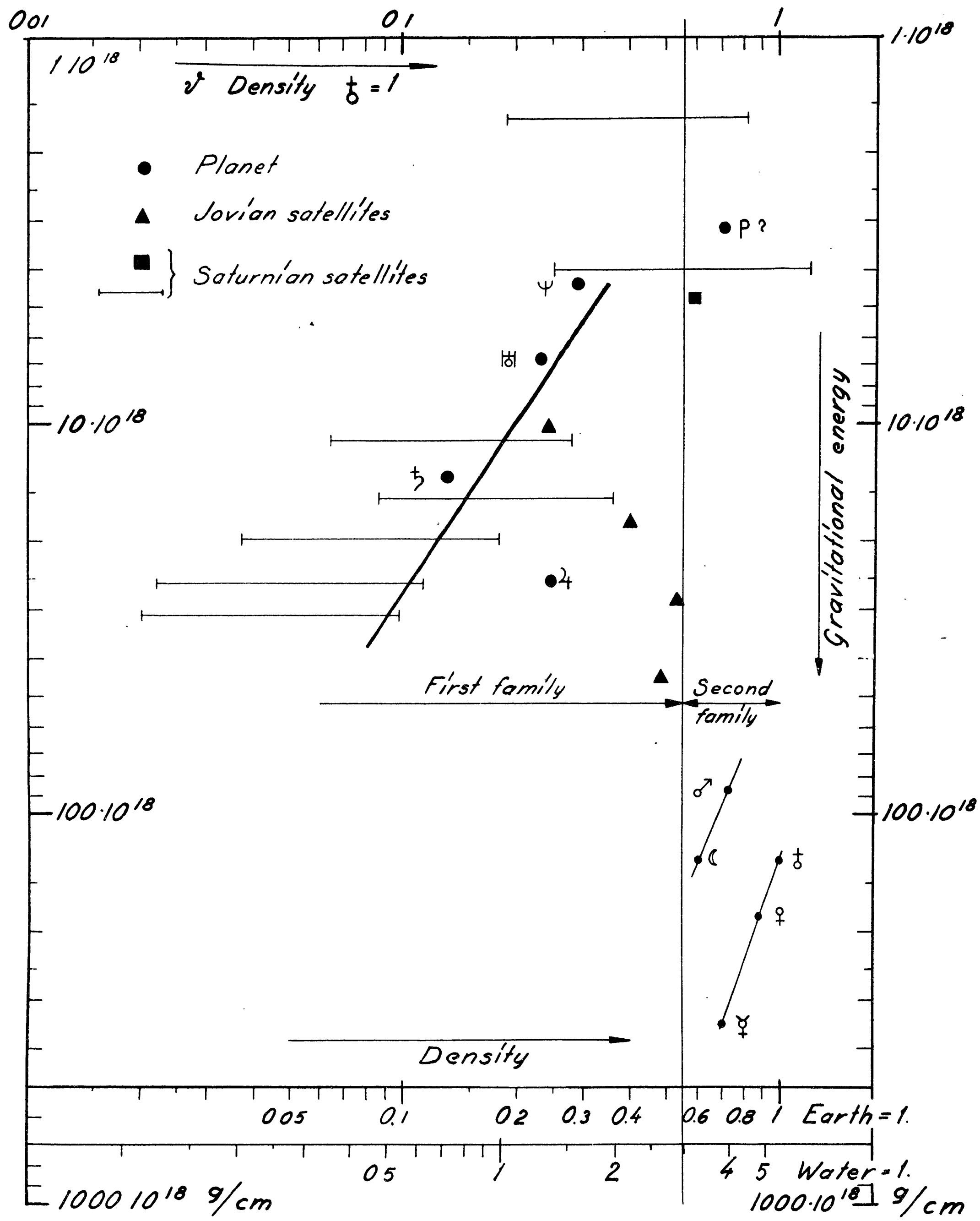

Fig. 12.

plotted. The diagram seems to indicate that the density depends in a systematic way on the gravitational energy. On the whole, *the density increases with decreasing gravitational energy* within every group of bodies.

Among the inner planets the density increases when we go outwards from Mercury to Venus and to the Earth. But if we go further, to Mars, the density decreases again. However, whereas Mercury, Venus, and the Earth have a genetical connection as shown by the fact that the q—Q-dots of Mercury-Venus and of Venus-Earth fall on the second family curve (Fig. 2), there is no such connection between Earth and Mars. The Earth-Mars dot is far away from both of the empirical $q—Q$-curves in Fig. 2. On the other hand, the Moon-Mars dot lies close to the second family curve, indicating a genetical connection. Thus there are reasons for dividing the inner planets (including Moon) into two groups: Mercury-Venus-Earth and Moon-Mars, and in both groups the density increases outwards.

The outer planets have, in general, densities which increase with decreasing gravitational energy. The only exception is Jupiter, but this may be due to its very large mass which is likely to cause so high a compression that the density of the matter increases.

The densities as far as they are known, of the Saturnian satellites seem to be about the same as those of planets with the same gravitational energy. The fourth Galilean satellite also lies on the same curve, but the three inner Galilean satellites form a noteworthy exception (See § 12).

If we take the increase in density with decreasing gravitational energy for granted, at least as a general rule, the question arises how to explain it.

When a gas cloud approaches the sun (or a planet) its temperature increases because gravitational energy is converted into heat. In Part I § 3 we have assumed that when the temperature has reached a certain limit, the cloud becomes ionized and is immediately stopped. Obviously the process cannot be so simple in reality, because the cloud is composed of a multitude of elements which have different ionization potentials. Consequently they become ionized at different temperatures. Thus we must expect a certain fractionating of the cloud in such a way that the lower ionization potential an element has the sooner it is stopped. Consequently, elements with low ionization potentials must dominate far away from the central body, whereas those with high ionization potentials must be more abundant closer to the central body. (Of course this holds only within the separate groups.)

The elements that are probably most abundant in the planetary system have the following ionization potentials:

N . . . . 14.5 volts	C . . . . 11.3 volts	Fe . . . . 7.9 volts
O . . . . 13.6 »	S . . . . 10.3 »	Ni . . . . 7.6 »
H . . . . 13.5 »	Si . . . . 8.1 »	Mg . . . . 7.6 »

The chemical combinations between the elements with high ionization potentials have usually small densities (e. g. H_2O: 1.0; CO_2: 1.5; NH_3: 0.64; CH_4: 0.42 in the liquid state), whereas in general those combinations, in which the elements with lower ionization potentials are constituents, are of high density (e. g. SiO_2: 2.3; FeS: 4.8; Fe: 7.9; Ni: 8.9; MgO: 3.6). Thus for the most abundant elements we can consider it as an approximate rule that the higher their ionization potentials the lower the density of the matter which they form.

The consequence of this is that the fractionating of the invading gas cloud must produce bodies with high density far away from the central body whereas lighter compounds are concentrated closer to the central body. For example, if the gas cloud approaching the sun contains iron and nickel, these elements are stopped at a larger distance from the sun than the rest of the cloud. We should expect to find most of them as a central core in Neptune and perhaps a small fraction even in Uranus. On the other hand Jupiter is likely to consist mainly of the elements with the highest ionization potentials, i. e. N, O, H and C.

To a certain extent the same phenomenon must occur also in the dust cloud. Here also there is an intermediate process between the volatilization of the primary dust particles and the ionization of the gas. A certain degree of fractionating in the same way as described above must also play an important part in this case.

Thus the general tendency that the density *(within a certain group)* increases with the distance from the central body can be explained in a rather simple manner.

C. On the origin of the solar system.

11. The »families».

Let us summarize the main results we have obtained.

The bodies of the solar system (sun excluded) can be divided into two »families». To the first family belong the giant planets and their »inner satellites» (Galilean satellites of Jupiter and Mimas—Rhea of Saturn). The second family includes the terrestrial planets and the »outer satellites» (Titan—Iapetus of Saturn and the four Uranian satellites). Some bodies with very small mass (e. g. retrograde satellites) do not belong to either of these groups or their identification is uncertain.

There are three independent arguments for the division of the bodies into two families.

1. The q—Q-values of adjacent planets or satellites fall on two different curves. See Fig. 2.

2. All the bodies of the first family have small densities (below 2.9) whereas the density of the bodies of the second family is always above 3.2. See Fig. 12 and Table 1.

3. The specific gravitational energy (with respect to the central body M) of the first family lies in the region $M/r = (0.5 - 5) \cdot 10^{19}$ g cm^{-1}. (Exception: for Neptune M/r is $0.44 \cdot 10^{19}$.) There is no member of the second family in this region.

The second family occupies the two regions $8 \cdot 10^{19}$—$40 \cdot 10^{19}$ g cm^{-1} and $0.1 \cdot 10^{19}$—$0.5 \cdot 10^{19}$ g cm^{-1}.

The first family is probably generated through the invasion towards the sun of a gas cloud containing mainly light elements. The condensation which proceeded from the outside inwards produced the giant planets, first Neptune and later Uranus, Saturn and Jupiter. Thereafter a remaining small fraction of it fell in towards these planets and, by a similar process, generated the »inner satellites» of Jupiter and Saturn.

The second family is probably due to a dust cloud consisting of small meteorites. Most abundant are some heavy substances (iron, nickel, silicates). Through the process outlined in I B it produced the inner planets and the »outer satellites».

The question now arises: did the gas cloud or the dust cloud appear first?

As the dust cloud has produced the outer satellites of Saturn and Uranus, these planets, originating from the gas cloud, must have already existed when the dust cloud arrived. Thus the dust cloud must have come later than the gas cloud. Consequently the terrestrial planets are younger than the giant planets.

There seems however to be an argument against this point of view. The Martian satellites give a q—Q-dot which lies close to the *first* family curve, so that they ought to have been produced by the gas cloud. On the other hand, their gravitational energy is much smaller than that which is usual in the first family. Their densities are unknown.

If we accept the conclusion that they are produced from the gas cloud, their central body — Mars — must have already existed when the gas cloud appeared. As there is a genetical connection between Mars and the Moon, as shown by their q—Q-dot as well as by their densities, the Moon too must have existed before the gas cloud.

This is not in contradiction with what is said above, because as we have seen there is no genetical connection between Moon-Mars and the Mercury-Venus-Earth group. Consequently it is likely that there have been two dust cloud invasions: the first previous to the gas cloud and responsible for the generation of the Moon and Mars; the second — after the gas cloud — generating Mercury-Venus-Earth (and the outer satellites).

This would also explain the lack of genetical connection between the Earth and Mars. According to this point of view it is fortuitous that the Earth has been produced so close to the already existing Moon that it has been able to capture it. (The violent fractures of the Moon's surface may be a reminiscence from the time when it witnessed the birth of the Earth.)

Thus there seems to be some indication that the genesis of the planetary system is due to the invasion of three clouds: first a dust cloud creating Moon and Mars, later a gas cloud responsible for the whole »first family», and finally a second dust cloud, producing the second family except Moon and Mars.

Our assumption of three clouds is not so artificial as might at first appear. The sun may have passed a complex interstellar cloud consisting mainly of gas but with a region of dust particles at its border. If so, there may have been one dust invasion when the sun entered and one when it left the cloud, and a gas invasion between these.

12. Some »irregularities» in the system.

It is of interest to endeavour to discover whether the three invasions were distinctly separated or interfered one with the other.

The first dust cloud produced the Moon and Mars much closer to the sun than the region where the gas cloud was stopped. Consequently, even if the gas cloud came immediately after the first dust cloud so that the condensation of this cloud was not completed before its arrival, it would not have interfered very much with the condensation process. If the first dust cloud already volatilized in part far away from the sun, it was accompanied by a heavy gas which must have been stopped at about the distance where Neptune and Pluto are situated. In this region there are two bodies — Pluto and the abnormal Neptunian satellite Triton — which may have been produced from the first dust cloud. On the other hand, they may also be due to the second dust cloud.

Thus it seems impossible to ascertain whether the gas cloud arrived immediately after the first dust cloud or not.

We have more hope of finding some results of an interference between the first family and the second dust cloud. If this arrived before the condensation of the first family bodies were completed, it must have passed the region where the condensation was progressing.

Of the bodies of the first family the outer planets condensed at first. Later on the Jovian and Saturnian satellites were produced. Although Saturn is older than Jupiter

— not only in the old myth — it is not certain that the Saturnian inner satellites are older than the Jovian satellites because the condensation may have gone swifter in the Jovian system. In any case, if the arrival of the second dust cloud has disturbed the condensation of the first family, this must have occurred in the Jovian or Saturnian satellite systems.

There is nothing remarkable in the Saturnian inner satellites: their q—Q-dots lie not too far from the first-family-curve (see Fig. 2) and their densities are, as far as is known, also in order. On the other hand, of the Jovian satellites the first three have densities which are higher than expected (see Fig. 12), and the q—Q-dot of the second-third lies rather much above all other dots.

Let us see if this could be due to an interference from the second dust cloud.

According to our general ideas the Jovian satellites have been formed through the invasion of the Jovian magnetic field by a gas cloud. When it has been ionized and caused to rotate, the condensation starts from outside. Thus the remotest satellite (IV) is produced at first. There is nothing remarkable in this body: its density ($= 1.32$) agrees well with the »normal» density curve (as found from the planets and Saturnian satellites with the same gravitational energy).

Suppose now that immediately after the formation of the fourth satellite the dust cloud invasion began. Thus, a multitude of dust particles (meteorites) impinged upon the rest of the gas cloud surrounding Jupiter. The meteorites captured by the cloud increased its mass and, what is especially important, its average atomic weight, so that its chemical constitution became intermediate between those of the first and second families. This would explain why the three innermost Jovian satellites which later condensed out of the cloud have densities intermediate between those of the gas cloud bodies and the dust cloud bodies. The intermediate character of these bodies is shown also by the fact that one of their q—Q-dots is intermediate between the first family and the second family curves in Fig. 2.

Of course meteorites were also captured by all the bodies (giant planets, Jovian fourth satellite) which were condensed already, but as their cross-sections are small, this capture was of little importance. For example, the diameter of a giant planet is about 10^{10} cm, so that its cross-section is of the order of 10^{20} cm^2. The gas cloud surrounding Jupiter after the formation of the fourth satellite had a diameter of about $\frac{3}{2} \cdot 20 \cdot 10^{10}$ cm (the third satellite has an orbital diameter of $20 \cdot 10^{10}$ cm), so that its cross-section was 10^{23} cm^2, which is 1000 times greater.

If the intermediate density of the first, second and third Jovian satellites is thus explained, the difference between the densities of the first and second families become much more pronounced. In fact in the first family the density does not exceed 1.58 whereas the smallest density in the second family is the double of that or 3.2.

Did the invasion of the dust cloud not affect the Saturnian system at all? As there is nothing irregular about the inner Saturnian satellites, the invasion certainly did not begin when the formation of the inner satellite system was progressing.

Then there are two possibilities: The system may have been completely formed when the invasion began. Then the dust cloud would not affect the satellites very much but probably disturb the regular structure of the ring. On the other hand it is also possible that the condensation had not yet started at all. If so, the meteorites would have been captured on the outer surface of the cloud surrounding Saturn.

The latter hypothesis would explain a remarkable irregularity of the Saturnian system, the existence of the giant satellite Titan (see Fig. 1). In the Uranian system the masses of the outer satellites increase, in general, with increasing distance from the planet, as is usually the case in satellite systems. The Saturnian outer satellite system ought to have been generated in the same way, so we should not expect so large a body as Titan at its inner end. If we assume that the formation of the inner Saturnian satellites had not started when the dust cloud arrived, the capture of meteorites at its outer surface would provide an extra mass of heavy substances which may later have condensed into Titan. Thus the mass of the outer Saturnian satellites might have been produced in two ways: in the »regular» way through the invasion of the heavy meteorite gas into the Saturnian magnetic field, and through direct capture of meteorites by the gas cloud surrounding Saturn.

If this hypothesis is correct the mass of dust particles captured by the Jovian and Saturnian systems ought to be proportional to their capture cross-sections. As the orbits of Titan and of the third Jovian satellite are about the same, almost the same mass would have been captured in both cases. Titan's mass is 0.024 (Earth = 1) and the total mass of the Jovian satellites I—III amounts to 0.046. As a fraction of the latter mass is due to the gas cloud, the matter captured from the dust cloud is about the same in both cases — as expected.

There are still some noteworthy irregularities in the planetary system. The Neptunian satellite Triton has not a normal character: it is very large and has a retrograde rotation. It was certainly not generated in the same way as other satellites, so we must suppose that it is a captured planet as our Moon. We have explained the curious features of the Earth-Moon system as due to a »joint» in the planetary system between the Mercury-Venus-Earth and the Moon-Mars groups. It seems likely that the Neptune-Triton system forms a similar »joint» between the giant planets and a system consisting of Triton and Pluto. The latter certainly does not belong to the Jupiter—Neptune group, for its size is too small and its density (probably) too high. As it has the same gravitational energy as the outer satellites it is reasonable to assume that it belongs to the second family so that it has been formed from the dust cloud. As was mentioned earlier, this could have occurred in such a way that the dust cloud (probably the second one) was accompanied by a heavy gas, produced through a partial volatilization of the dust at a distance far from the sun. This gas was of the same constitution as that responsible for the production of the outer satellites, so that it must have been stopped about where Pluto and the Neptunian system are now found. Consequently it could very well have formed Pluto and Triton. The latter was formed so close to Neptune that it was captured.

If this hypothesis is correct the density of Triton must be high (about 4) which may perhaps be checked by observations.

13. Other factors affecting the structure of the solar system. Changes in sun and system.

Even if we accept the general ideas proposed in this paper it is obvious that other effects have also influenced the structure of the solar system.

The asteroids show very pronounced gaps at those places where their periods would be an integral fraction of Jupiter's. In the same way the inner Saturnian satellites have produced faint dark markings on the Saturnian ring system. In both cases gravitational resonance effects have been in action. Such has also been the case in the Jovian and the Saturnian satellite systems where some of the satellite periods are commensurable.

Probably it is not necessary to assume that such effects have been very important during the formation of the system. If so, the commensurability of the Jovian satellites, for example, is mostly fortuitous. The density of the ionized matter of which they were formed happened to have such a density distribution that, according to the general laws governing the condensation, the satellites were formed at such places that their periods were not very far from commensurability. Owing to the gravitational forces the approximate resonance was transformed into an exact resonance.

In many cosmogonies a great importance is attributed to a supposed change in the chemical constitution of planets due to volatilization of the most volatile substances.

For example, the difference in density between the outer and the inner planets has been explained through the assumption that the gravitation of the latter has not sufficed to retain the lighter substances. In this way it is not possible to explain the very low densities of the inner Saturnian satellites, which according to this view ought to have extremely high densities. According to our ideas there is no reason to suppose that any *major* changes in the mass or constitution of planets or satellites have taken place since their formation. Of course minor changes have occurred, such as the disappearance of the Moon's atmosphere. Furthermore the axial rotations have no doubt been changed through tidal friction.

In general the planetary system had probably about the same state immediately after its formation as it has now. Even the Sun's state at the time of the formation of the solar system might very well have been *about* the same as its present state, so that there is apparently no need to assume any connection between the formation of the planets and the general cosmogony of the stars.

In two respects, however, the breeding Sun must have differed from the Sun of today. It must have had a larger rotational moment and probably also a larger magnetic moment. Before the clouds generating the planets arrived, the whole rotational moment of the present planetary system must have been possessed by the Sun. In order to transfer the greater part of this moment to the planets and also to support the matter during the formation it must have had a strong magnetic field. It is difficult to calculate exactly what the Sun's dipole moment must have been, but it probably exceeded the present value by several powers of ten.

Stockholm, May 1942. K. Tekniska Högskolan.