

ON THE EARLY HISTORY OF THE SUN AND THE FORMATION OF THE SOLAR SYSTEM

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ABSTRACT

It has earlier been shown that the mass distribution within a group of secondary bodies (e.g., satellites) formed around a central body is a function of the rotational velocity of the central body. From a study of the satellite groups an empirical relation was derived, which makes it possible to find the rotational velocity of a central body when the mass distribution of the secondary bodies is known. This result is applied to the terrestrial planets. It appears that when the Mercury-Venus-earth group was formed, the rotational period of the sun was about 20 days. As this agrees reasonably well with the present value, it is tempting to conclude that the terrestrial planets were formed *after* the giant planets, at the formation of which the sun lost most of its angular momentum. However, arguments are given for an alternative view, viz., that the terrestrial planets were formed *before* the giant planets and that both processes took place when the sun was in the deuterium-burning state. If this alternative is accepted, *we can calculate the present period of the solar axial rotation* in good agreement with the observed value.

I. STELLAR EVOLUTION AND THE FORMATION OF THE SOLAR SYSTEM

The study of the early history of the sun has so far been based on the general theory of stellar evolution. The theoretical foundation of this is a stellar model in which the generation of energy is due mainly to nuclear reactions. The observational foundation is connected with the Hertzsprung-Russell diagram.

Independently of this, the formation of the solar system has been studied with magnetohydrodynamics and plasma physics as the theoretical foundations and the properties of planets and satellites as observational data. A general theory has been developed which treats the formation of secondary bodies around a central body, and this theory has been applied to the generation of planets around the sun, and satellites around a planet (Alfvén 1954, 1962; Alfvén and Wilcox 1962). It must be assumed that the central body possesses a magnetic dipole moment exceeding a certain limit, but the actual value of it does not enter in the theory. It has been shown (Alfvén 1962) that under these conditions the structure of a system of secondary bodies is determined by two parameters: (1) the mass of the central body, and (2) the rotational period of the central body.

The study of the generation of secondary bodies around a central body has been based essentially on the properties of the satellite systems. In the development of the theory it is not necessary to introduce any more specific assumption about the properties of the sun during the formation of the solar system. A consequence of this is that if we apply the theory to the formation of planets around the sun, we can draw important conclusions about the properties of the sun at the time when the solar system was formed.

The purpose of this paper is to try to connect the properties of the early sun, derived from the theory of stellar evolution, with the properties derived from a study of the formation of the planetary system. In this way it may be possible to obtain more information about the early history of the sun and the solar system.

II. THE EARLY HISTORY OF THE SUN

The formation of the sun out of a dilute magnetized cloud has been treated by Spitzer, Mestel, and others (see Mestel 1960). The immediate result of the process is a very large star, which at first radiates the energy produced by contraction. When the contraction

proceeds, the central temperature will reach a value that is sufficient for the burning of the deuterium which the sun contains.

§ When this state is reached, which occurs when the solar radius is 10–20 times the present radius, the contraction is slowed down, and the sun has a more or less constant radius during a certain time. When most of the deuterium is burned, a new contraction takes place, which brings the sun to the present state, characterized by the burning of hydrogen.

¶ It is uncertain how long a time the sun spends in the deuterium-burning state. This depends upon how much deuterium the initial sun contained and also whether the energy transport was convective or not. Under the assumptions that the initial content of deuterium corresponds to the D/H ratio at the earth and that the energy transport in the deuterium-burning sun is non-convective, Brownlee and Cox (1961) have calculated a model of the development of the sun, which is shown in Figure 1. The radius of the sun

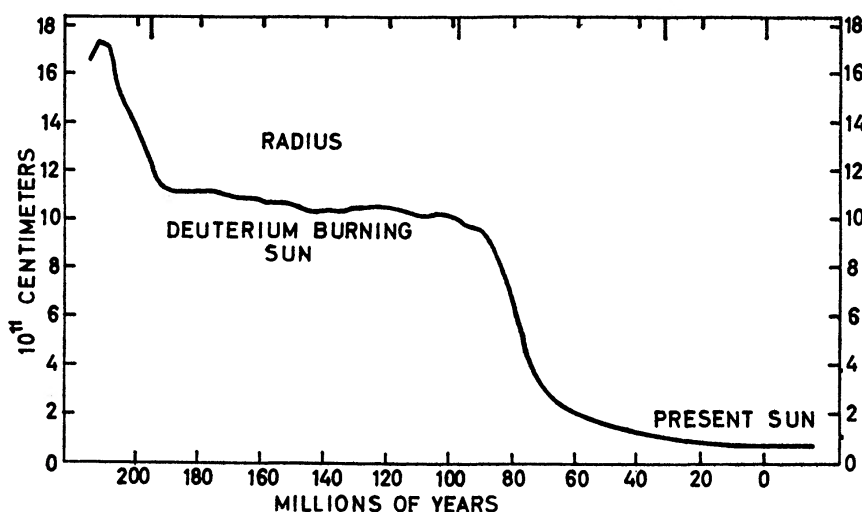


FIG. 1.—Development of the sun (Brownlee-Cox) under the assumption of a non-convective model

is 16 times the present radius during a time of about 10^8 years. A different initial content of deuterium (which is possible) would mainly change the time which the sun spends in the deuterium-burning state.

If the deuterium-burning sun were convective, the plateau would be reached at a somewhat smaller radius, the time that the sun spends on the plateau would be shorter, and the plateau not so well pronounced. It is possible that under the assumption of a non-rotating and non-magnetized sun a convective model would be preferable (Brownlee, private communication). However, both the rotation and the magnetization (which both for other reasons must have been rather large) tend to counteract the convection; so at present no decision between the models is possible. We shall use the Brownlee-Cox model for the discussion here; but, with a slight modification, our results will be applicable also to a convective model.

The deuterium-burning sun was likely to have a large *magnetic dipole moment* because it had been formed from a magnetized cloud. Consider a sphere that has the radius R and a homogeneous magnetization H_p . The flux $\phi = \pi R^2 H_p$ should remain constant when the sphere contracts. Its dipole moment a is given by

$$a = \frac{H_p}{2} R^3 = \frac{\phi}{2\pi} R. \quad (1)$$

If the sun derives from a cloud with the radius $R_0 = 10^{18}$ cm and the magnetization $H_p = 10^{-6}$ gauss (both conservative values), we have $\phi = 3 \times 10^{30}$ gauss cm². As its radius is about 10^{12} cm, the deuterium-burning sun should have a dipole moment of the order of $a = \frac{1}{2} 10^{42}$ gauss cm³, corresponding to a polar field strength $H_p = 10^6$ gauss. This is an unreasonably high value, and the sun must have lost magnetization by some process that is not very well understood (cf. Mestel 1960).

For the formation of the planetary system it is essential that the sun have a dipole moment exceeding a certain value ($a \geq 10^{38}$ gauss cm³), but the actual value does not enter explicitly in the theory (Alfvén 1954). As the limiting value is much lower than what was derived above, it seems legitimate to assume that this requirement is fulfilled.

In the studies of the early development of the sun it is usually assumed that the mass of the sun has had approximately its present value. We accept this view because the mass accumulation during the formation of the planets is likely to have been much smaller than the solar mass.

The *angular momentum* of the sun has changed very much because, when the giant planets were formed, the sun must have transferred a fraction $1 - a = 0.994$ of its angular momentum to orbital moments of these bodies and retained only a fraction $a = 1/180$. The transfer is likely to have been produced by a hydromagnetic process (compare Lüst and Schlüter 1955). In connection with the formation of the initial sun from a primeval cloud, there is the problem of how the sun has got rid of most of the enormous angular momentum that the cloud is likely to have possessed. It seems likely that the loss of angular momentum took place at a very early state when the hydromagnetic coupling between the primeval cloud and the surroundings was strong and that no considerable loss took place later. We shall not discuss this process but only make the reasonable assumption that, during the period we consider, the total angular momentum of the solar system was constant.

III. THE ANGULAR VELOCITY OF THE SUN CALCULATED FROM THE MASS DISTRIBUTION IN THE PLANETARY SYSTEM

As an analysis has shown, the mass distribution within the satellite groups depends in a characteristic way on the period T of axial rotation of the central body (Fig. 2). The important parameter is the ratio τ_i/T , where τ_i is a sort of average of the Kepler periods of the satellites in the group. More exactly defined, τ_i is the Kepler period of a body at the ionization limit. If τ_i/T has a high value (e.g., 100 or 1000), the mass of the bodies in a group decreases outward; if τ_i/T is about 25, all the bodies have approximately equal mass, whereas if τ_i/T is less than 10, the masses increase rapidly outward (compare Fig. 2).

If we apply this result to the groups of planets, we can derive the value of τ_i/T , and, as τ_i is known, we can calculate the period T of the solar axial rotation at the time when the group in question was formed. For this purpose we introduce the masses of the planets in the diagram of Figure 2. Comparing the slope of the Mercury-Venus-earth line with the corresponding lines for the Uranian satellites and the inner Saturnian satellites, we find that the terrestrial planets are intermediate between the values for the Uranian satellites and the inner Saturnian satellites. As for the Uranian satellites $\tau_i/T = 12$, and for the inner Saturnian satellites $\tau_i/T = 8$, we conclude that at the formation of the terrestrial planets the value of τ_i/T was between 8 and 12, or, say, $\tau_i/T = 10$. As $\tau_i = 0.56$ year, we find the period at the arrival of the B cloud to be $T_B = 0.056$ year = 20 days. This is close to the present period of the axial rotation of the sun, which is 25 days. From this we conclude that the sun rotated with approximately its present angular velocity when the group earth-Venus-Mercury was formed.

As has been shown elsewhere (Alfvén 1954), the moon is likely to have been a planet originally, which was later captured by the earth. It belonged to the same group as

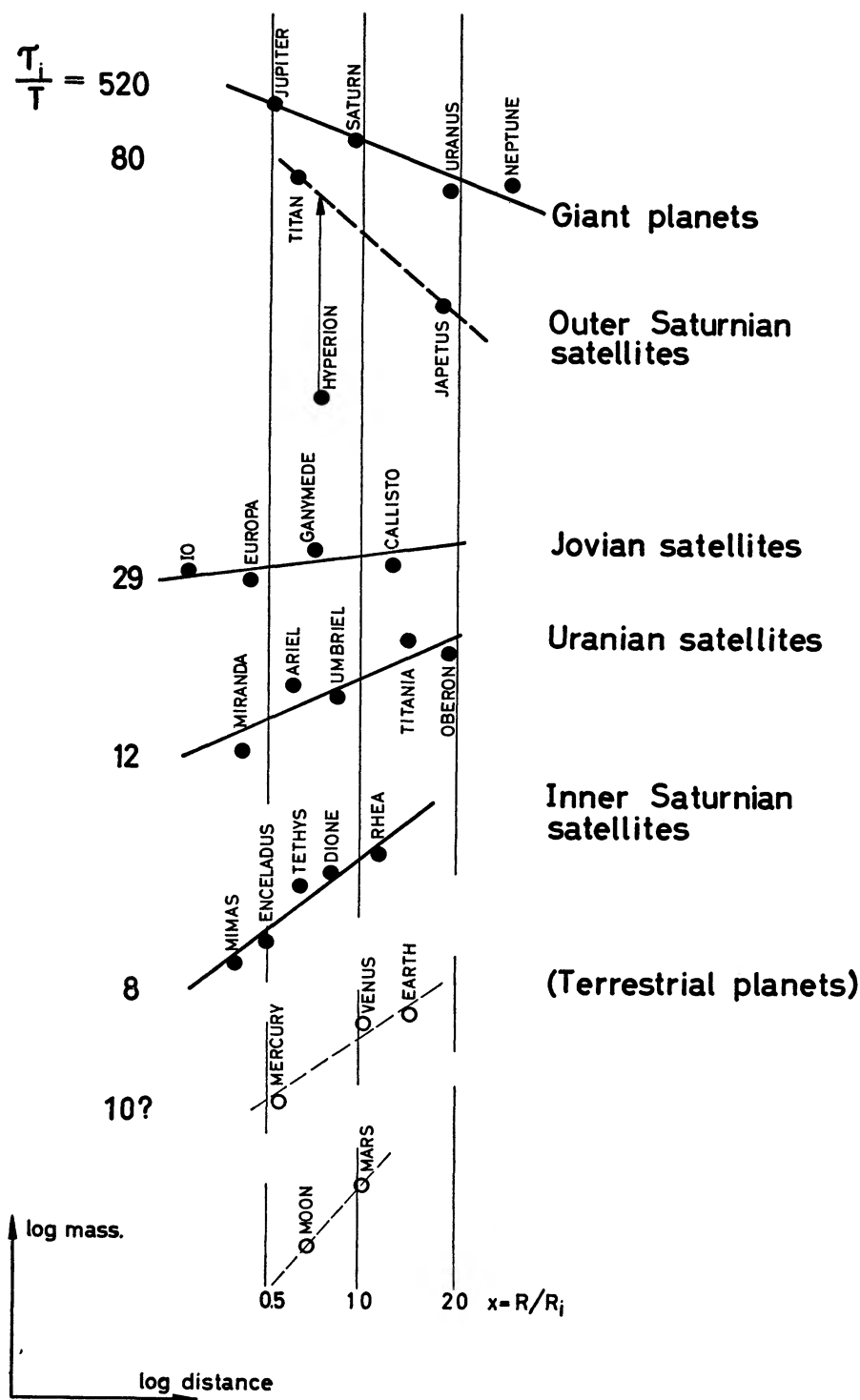


FIG. 2.—Mass of the bodies as a function of the distance x from the central body. The distance is normalized; $x = R/R_i$, where R_i is the ionization limit (= distance where the critical velocity is reached). To the left the ratio τ_i/T for each group. τ_i is an average of the Kepler periods of the bodies and T the period of axial rotation of the central body. The diagram shows that the mass distribution within a group varies in a systematic way with τ_i/T . In the lower part of the figure the Mercury-Venus-earth group and the moon-Mars group are included. The slope of the first group is seen to be intermediate between the slopes in the Uranian and inner Saturnian groups and is hence estimated to corresponding to $\tau_i/T = 10$. It is doubtful whether any conclusions should be drawn from the moon-Mars group (possibly $\tau_i/T \approx 4$).

Mars and was formed at the same time. If in Figure 2 we draw a straight line between the dots representing the moon and Mars, we find that the slope is somewhat steeper than for the inner Saturnian system. This indicates that the τ_i/T value at the time of formation was lower than 8, which is the value for the inner Saturnian satellites. On the other hand, the value must be definitely higher than for the rudimentary group, which contains only the fifth Jovian satellite. This group has $\tau_i/T = 1.6$. Let us adopt the intermediate value $\tau_i/T = 4$ for the Mars-moon group. As $\tau_i = 1.84$ years, we obtain $T_A = 0.46$ year = 170 days. This result is obtained under the somewhat doubtful assumption that the conditions in the Mars-moon group have not been changed very much by the capture of the moon. Among other things, this implies that the solar distance of the planet moon before it was captured by the earth was equal to the earth's distance. Hence we need not necessarily pay much attention to the result of this calculation.

For all groups of planets and satellites, except the giant planets, the total orbital momentum of the bodies is small compared with the angular momentum of the central body. Hence the formation of the bodies did not change the period T appreciably. The giant planets, on the contrary, have a total orbital momentum which is $1/a = 180$ times the present angular momentum of the rotating sun. Consequently, when they were formed, the angular velocity of the sun changed from a high value, $\Omega_1 = 2\pi/T_1$, to a much lower value, $\Omega_2 = 2\pi/T_2$. Hence the mass distribution-curve is a superposition of curves of different τ_i/T values. However, the curve should roughly correspond to some average value, which, as $\Omega_2 \ll \Omega_1$, could be put approximately equal to $\frac{1}{2}\Omega_1$. Hence the mass distribution of the giant planets should roughly correspond to $\frac{1}{2}\tau_i/T_1$, where T_1 is the solar angular velocity just before the giant planets were formed.

The Jovian satellites ($\tau_i/T = 28$) have approximately equal masses. As, for the giant planets, the masses decrease outward, they should have a much higher τ_i/T value—say $\tau_i/T > 50$ or perhaps $\frac{1}{2}\tau_i/T_1 > 50$. As $\tau_i = 30$ years, we find, for the solar rotational period before the production of the giant planets, $T_1 < 0.3$ year, a relation which, for other reasons, seems likely to be satisfied. Hence we cannot draw any important conclusions from an analysis of the mass distribution of the giant planets. The reason is that their τ_i/T value is close to “infinity,” i.e., so high that a variation does not affect the mass distribution.

Thus the conclusion from our analysis is that, at the arrival of the A cloud which produced Mars and the moon, the sun had a period which may have been $T_A = 170$ days, but this value is uncertain.

At the arrival of the B cloud, from which the earth, Venus, and Mercury originated, the period was $T_B = 20$ days, which is very close to the present value. Because the sum of the orbital moments of the terrestrial planets is small compared with the angular momentum of the sun, no appreciable change in the solar rotational velocity was produced by the transfer of angular momentum to these clouds.

It is impossible to deduce the angular velocity of the sun when the C cloud arrived, but, as the total orbital momentum of the giant planets is $1/a = 180$ times the present angular momentum of the sun, the solar angular velocity decreased by a factor of 180 at the formation of the giant planets.

IV. ON THE TIME OF ARRIVAL OF THE CLOUDS

It is tempting to conclude that both the B -cloud and the A -cloud planets were formed after the giant planets when the sun had reached its present angular velocity. This would imply that we do not give any significance to the difference between the present solar rotational period and the period derived from the A -cloud mass distribution (which is based only on the Mars-moon relation). However, this conclusion meets the objection that it would be difficult to understand how the C cloud could have arrived before the A and B clouds (cf. Alfvén 1954).

If, instead, we accept that the C cloud arrived later than the A and B clouds, we

must conclude that, at the arrival of the B cloud, the angular momentum, $\theta_B\omega_B$, of the sun must have been a factor $1/\alpha = 180$ larger than the present value $\theta_p\omega_p$ (θ , ω , and T mean moment of inertia, angular velocity, and period of rotation; index A and B represent conditions at the arrival of the A and B clouds; index p the present values). Hence we obtain

$$\frac{\theta_B}{\theta_p} = \frac{\omega_p}{\omega_B \alpha} = \frac{T_B}{T_p \alpha} = \frac{20}{25} \times 180 = 144, \quad (2)$$

where we have introduced the value of T_B from Section III.

Assuming a similar internal mass distribution, equation (2) means that the solar radius was $\sqrt{144} = 12$ times the present value when the B cloud arrived. This agrees rather well with the radius of the deuterium-burning sun. In fact, the Brownlee-Cox model gives a radius of $16 R_\odot$ (a convective model probably somewhat smaller). A detailed calculation of the moment of inertia of the Brownlee-Cox model gives 200 times the present value (Brownlee, private communication).

If this agreement is more than a coincidence, our conclusion should be that the B cloud arrived when the sun was in the deuterium-burning state. Following up this line of approach, we could very well attribute significance to the larger period $T_A = (0.45 \text{ year})$ derived from the A cloud. This period, which is 7 times the period at the arrival of the B cloud, would mean that, at the arrival of the A cloud, the moment of inertia of the sun was 7 times larger than during the deuterium-burning state. This implies that the A cloud arrived before the sun had reached the deuterium-burning state and had a radius of $\sqrt{7}$ times the radius of the deuterium-burning sun, or about $3 \times 10^{12} \text{ cm}$. As mentioned above, the foundation of this conclusion is not very strong.

Figure 3 shows a diagram of the changes in the angular velocity of the sun. The diagram gives two alternatives: the C cloud arrived either when the sun was in the deuterium-burning state ("first alternative") or when it was in the present state ("second alternative"). The decision between these two alternatives will be made in the following section. (Of course it is also possible that the D cloud arrived during a long time, beginning in the deuterium-burning period and ending in the present period.)

V. C CLOUD ARRIVES AFTER THE DEUTERIUM-BURNING PERIOD OF THE SUN

To take the second alternative first, this means that the sun had a rotational period of about 20 days during the whole deuterium-burning period. When it contracted to its present state, the angular velocity went up by a factor $\theta_B/\theta_p = 144$, which means a period of 0.14 day or 3.3 hours. Then the C cloud arrived, and the sun transferred 99.4 per cent of its angular momentum to it, so that its angular velocity went down by a factor $1/\alpha = 180$, and the present period was obtained. A serious objection to this alternative is that we cannot see why the sun transferred exactly $1 - \alpha = 99.4$ per cent of its angular momentum to the giant planets.

The Galilean satellites of Jupiter have a total orbital moment that is about 0.01 of the rotational momentum of Jupiter. The satellites were formed out of a cloud that was stopped at a certain distance, and the total mass of the satellites is given by the mass that was stopped. At the present state of development of our theory, we cannot compute how much mass the C cloud around Jupiter should contain; so, in order to account for the mass of the satellites, we must make an *ad hoc* assumption that just so much mass fell down toward Jupiter. If instead, say, three times more mass had fallen down, the satellites would have been three times heavier, and Jupiter would have transferred 0.03 of its angular momentum in order to put them in orbit.

In the case of the giant planets it seems very unlikely that their size should be determined by the mass of the cloud which fell down toward the sun because this would imply that the mass was exactly so large that 99.4 per cent of the angular momentum

was necessary to put it into orbit (cf Fig. 4). If only a little more mass had fallen down, the sun would have transferred all its momentum to the giant planets, and the solar rotation would have been braked completely, or, to be more exact, co-rotation would have been established between the sun and the cloud out of which the giant planets were formed. As Jupiter is the innermost and largest of the giant planets, the result would have been that the solar period of axial rotation would have been the same as Jupiter's

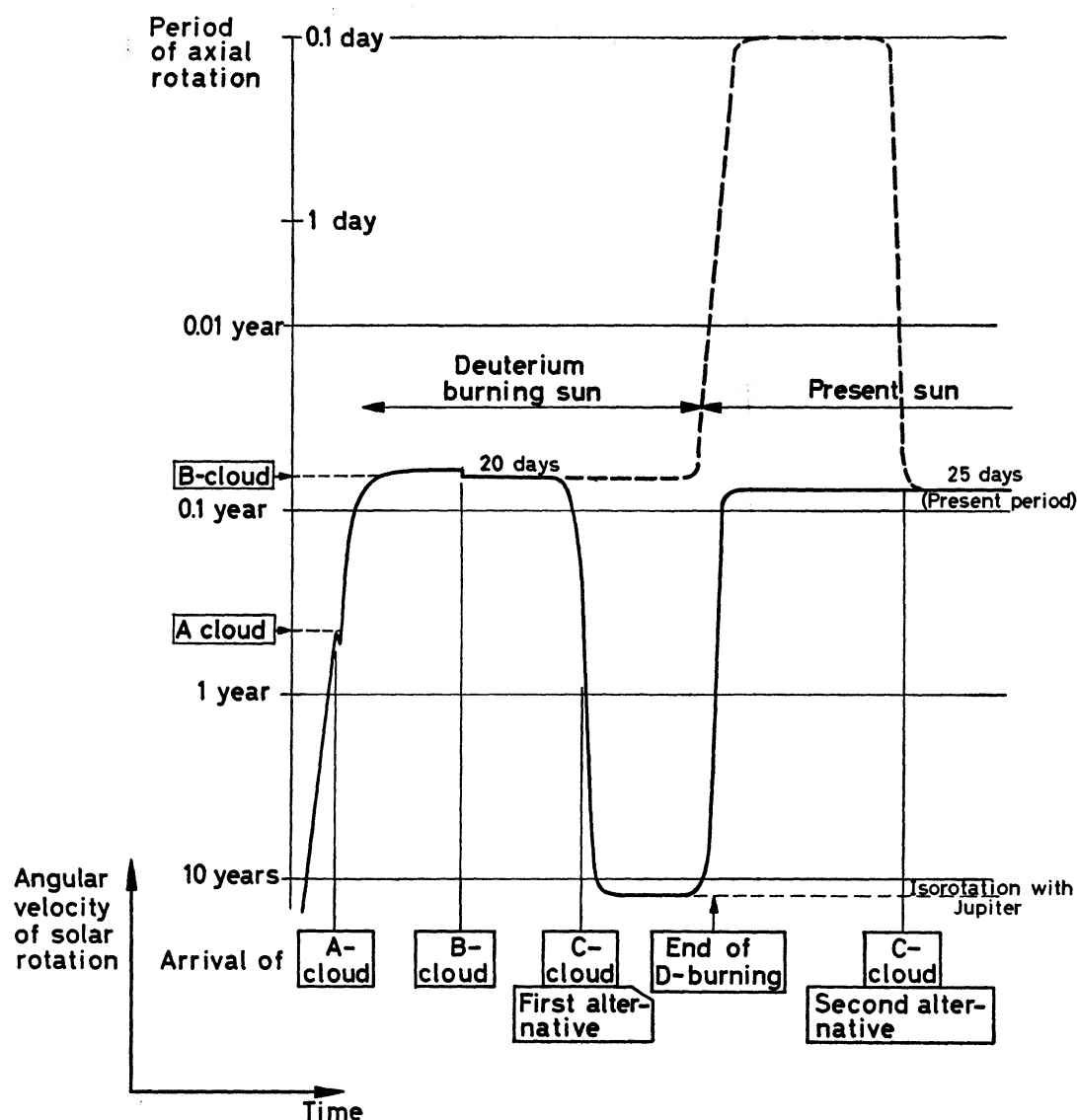


FIG. 3.—Angular velocity of the sun as a function of time. It is assumed that the solar system does not lose any angular momentum to infinity. As the sun contracts, its moment of inertia decreases, so that its angular velocity increases. The contraction is small during the deuterium-burning period, and the angular velocity remains constant. The *B* cloud (forming the earth, Venus, and Mercury) arrives during this period but does not change the angular velocity appreciably. (The *A* cloud may have arrived earlier.) When the *C* cloud (forming the giant planets) arrives, the sun loses most of its angular momentum and is brought to isorotation with Jupiter (period 12 years). When the deuterium is burned out, the sun contracts to its present state, which means that the moment of inertia goes down by a factor of 200. The angular velocity goes up by the same factor, and in this way the present angular velocity of the sun is determined.

Kepler period, or about 12 years. This represents a saturation value, so that if, say, three times more mass fell down, the solar rotation would also coincide with Jupiter's period.

VI. *C* CLOUD ARRIVES DURING THE DEUTERIUM-BURNING PERIOD OF THE SUN;
CALCULATION OF THE PRESENT ROTATIONAL PERIOD OF THE SUN

We shall now turn to the first alternative, viz., that the *C* cloud arrives when the sun is in the deuterium-burning state. As the sun has transferred most of its momentum to the giant planets, it is natural to assume that the total mass which arrived was so large that a state of saturation was reached, and the solar rotational period had become equal to Jupiter's orbital period (12 years). This does not imply any specific assumption about the total mass of the *C* cloud. It must have exceeded the total mass of the giant

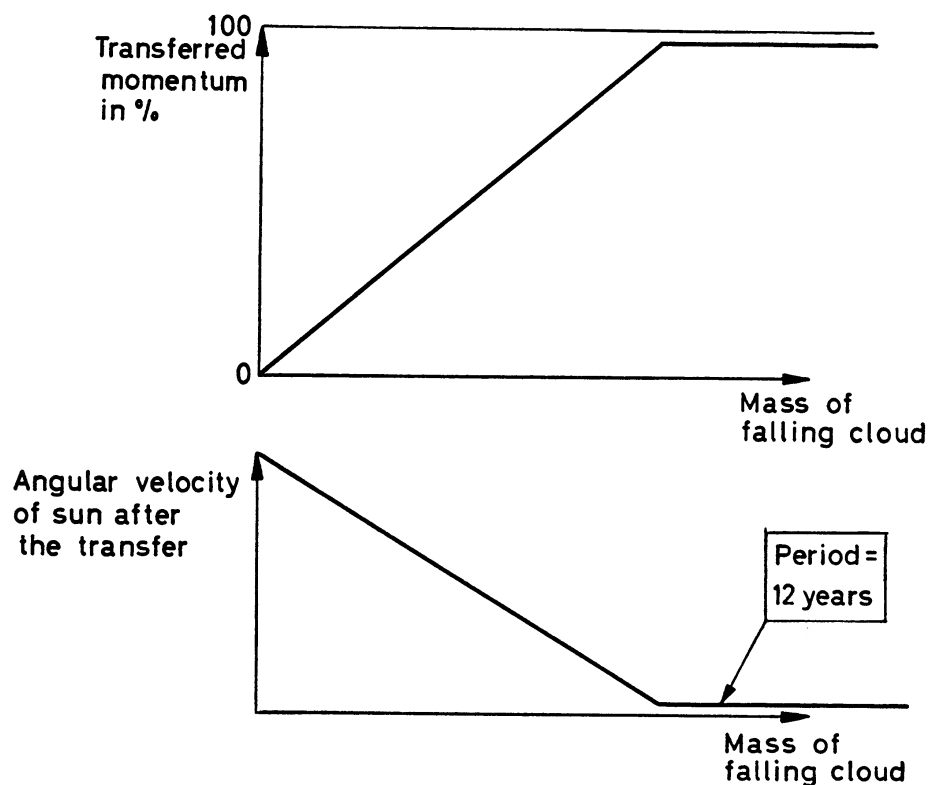


FIG. 4.—*Above*: Angular momentum transferred to the *C* cloud as a function of the mass of this cloud. The momentum is proportional to the mass until a saturation is reached, when almost the whole momentum is transferred. *Below*: Angular velocity of the sun after the transfer. When saturation is reached, the solar angular velocity equals the Kepler velocity of Jupiter. If the transfer takes place when the sun is in the deuterium-burning state with a moment of inertia 200 times the present value, the angular velocity goes up by a factor of 200 when the sun contracts, which explains the present angular velocity of the sun.

planets, but it is unimportant whether the mass of the cloud was twice or ten times the mass of the present planets. In both cases the giant planets would grow in size until the sun had lost practically all its angular momentum. If when this state is reached, more gas falls down, it will certainly be ionized at the ionization limit; but, as the τ_i/T value has gone down to unity, the gas will not be brought into orbit but fall down along the magnetic lines of force to the sun.

If the whole C cloud (and also the D cloud) arrived before the end of the deuterium-burning period, the solar system was formed and was essentially in the same state as now, with the important difference that the sun had 10–20 times the present radius, a rotational period which equals the orbital period $T_{\mathcal{A}}$ of Jupiter, and a moment of inertia θ_e which should equal the value θ_B which we calculated in Section IV. When later, by contraction, the sun reached its present state, its moment of inertia diminished from θ_B to θ_p . The result is that the sun's axial rotation gets the period

$$T_p = T_{\mathcal{A}} \frac{\theta_p}{\theta_B}. \quad (3)$$

If we introduce the value $\theta_B/\theta_p = 200$, which Brownlee and Cox have calculated for the deuterium-burning sun, we obtain, with $T_{\mathcal{A}} = 12$ years,

$$T_p = \frac{12}{200} = 0.06 \text{ year} = 22 \text{ days},$$

in satisfactory agreement with the present period of 25 days.

Hence, if we choose the first alternative, we are able to understand how the sun has got its present rotational period. This speaks strongly in favor of this alternative.

VII. DISCUSSION AND SUMMARY

Our analysis has shown that the planetary system was probably produced at a time when the moment of inertia θ_B of the sun was much larger than the present value θ_p . The value of θ_B can be calculated in two independent ways. According to Section III, we have

$$\frac{\theta_B}{\theta_p} = \frac{T_B}{\alpha T_p},$$

where T_p is the present value of the solar rotational period and α is the ratio between the present angular momentum of the sun and the total angular momentum of the solar system; T_B is derived from the analysis of the mass distribution within the terrestrial planets (Sec. III). With $T_p = 25$ days, $T_B = 20$ days, and $\alpha = 1/180$, we obtain $\theta_B/\theta_p = 144$.

Further, we can calculate θ_B/θ_p from equation (3):

$$\frac{\theta_B}{\theta_p} = \frac{T_{\mathcal{A}}}{T_p},$$

where $T_{\mathcal{A}}$ is a weighted mean of the periods of the giant planets, which probably is close to the Kepler period of Jupiter. With $T_{\mathcal{A}} = 12$ years and $T_p = 25$ days, we obtain $\theta_B/\theta_p = 175$. Both values are in reasonable agreement with the moment of inertia $\theta_B = 200 \theta_p$ calculated by Brownlee and Cox for the deuterium-burning sun under the assumption of a non-convective model. (A convective model will probably give a somewhat smaller value.)

This suggests that when the sun had reached its deuterium-burning state, the conditions for the formation of a planetary system were favorable. Remnants of the initial cloud from which the early sun had condensed fell in toward the sun, and, as a certain chemical differentiation had taken place, the falling gas was stopped at different distances from the sun, forming the groups of planets.

It is possible to calculate the axial rotation and the minimum magnetization of the deuterium-burning sun. As these quantities are important for a detailed solar model, they should be taken into account. They may be of decisive interest for the question whether the state was convective or not.

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