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Earth and Moon: Past and Future

Astronomical observations and dynamical arguments place new limits on theories of the origin of the moon.

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The origins of the earth and moon and the course of their histories must be included among the great problems of natural philosophy, comparable in general interest to questions regarding the origin of life and the development of man. The imminent prospect of exploring earth's nearest neighbor further heightens interest in this ancient problem. A multitude of new studies, as well as the revival of older theories, demonstrates the renewed concern with cosmology.

Today, the earth and moon form a close partnership, accompanying each other in a monotonous journey about the sun. But, one may ask, for how long has this partnership existed? Does the earth-moon system date from the early stages of the evolution of the solar system, or is it a more modern development?

Answers to these questions involve the dynamics of the earth, moon, and sun, and, to a much lesser degree, the other planets. In principle, it is possible to begin with the present position of the members of the solar system and trace the changes in their orbits back in time. Such a program requires a detailed understanding of how the individual members of the solar system interact with each other. The greater part of the interaction can be described in terms of point masses attracted to one another by gravitational forces. In the case of many point masses, we have only a primitive understanding of the dynamic consequences of the interactions.

Since the classic work of George Darwin it has been known that there is another kind of gravitational interaction, dependent both on the deformability of planets and satellites and on the existence of friction (*1*). The frictionally retarded tides influence the long-term evolution of the orbital elements of a satellite, and of the rotational parameters of a planet. Indeed, it appears that tidal-frictional effects dominate the dynamics of the inner planets, while many-body interactions may have affected the evolution of the major planets and their satellite systems (*2*).

In this article I consider the following problem. At present the motion of the moon and the rotation of the earth are specified by a finite set of parameters. Owing to tidal friction, these parameters change with time. What range of initial conditions could yield the present state of the earth-moon system? The time scale over which the present earth-moon system has evolved presents a further question: Is this time scale compatible with the known age of the solar system?

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Mechanics of Tidal Friction

We first suppose the earth to have perfect elasticity in its solid parts and perfect fluidity in its liquid parts. With these conditions, the region of maximum height of the tide raised by the moon lies directly under that body (see Fig. 1, top). The maxima in the tidal protuberances, both toward and away from the moon, lie along the line of centers of the earth and moon. Because of symmetry, the moon does not perturb the rotation of the earth, nor do the tides produce a long-term change in the orbital elements of the moon.

If friction accompanies the deformation, then the rotation of the earth carries the lagging tidal bulge forward. The tide is not high when the moon is directly overhead, but is high at some later time (see Fig. 1, bottom). The gravitational attraction on the bulge is asymmetrical with respect to the line of centers; the asymmetry gives rise to a torque on the earth, tending to decelerate the earth, and an equal and opposite torque on the moon, tending to accelerate the moon. The action of the torque results in a transfer of angular momentum from the rotation of the earth to the orbital motion of the moon. Because of friction, this transfer is accompanied by a loss of the mechanical energy of the earth-moon system.

In general, the moon does not lie in the equatorial plane of the earth, so the tidal bulge is asymmetric with respect to the equator. As a result, there is a component of the torque tending to tip the orbital plane of the moon and an equal and opposite component tending to change the direction of the earth's axis of rotation. Figure 2 illustrates this point. The moon moves in the plane x_1, x_2, with angular velocity n represented by the vector $\mathbf{n}$ along the x_3 axis. Line *OP* is drawn perpendicular to the ecliptic, the common plane of the earth and sun. In our discussion we assume that the orientation of the ecliptic remains constant in

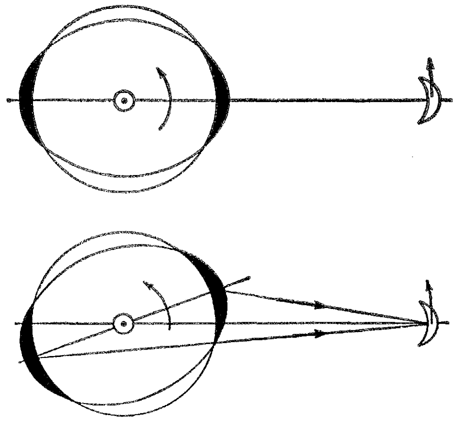


Fig. 1. (Top) The tidal bulge, if there is no friction. The bulge is symmetrical with respect to the line of centers between the earth and moon. If there is friction there is a delay in the time of high tide. The resulting distortion of the tidal bulge (diagram at bottom) leads to a torque, diagrammatically illustrated. The torque decelerates the earth's rotation and accelerates the moon's orbital motion.

time, recognizing that there are short-period wobbles due to the aforementioned many-body effects. Both the moon's orbital plane and the earth's axis of rotation, Ω, are inclined with respect to the ecliptic. The former is at angle I, the angle of inclination, while the latter is at angle γ, the angle of obliquity. The tide on the earth, raised by the moon, is carried out of the orbital plane of the moon by the rotation about Ω. Since the tidal bulge does not lie in the plane x_1, x_2, there is, on the average, a torque tending to change both the inclination I and the obliquity γ.

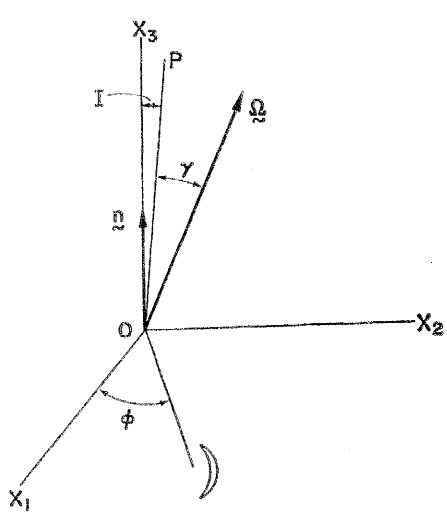


Fig. 2. Diagrammatic representation of the inclination, I, of the moon's orbit and the obliquity of the earth's equator to the ecliptic, γ. The line OP represents the perpendicular to the ecliptic.

The most important feature about tidal friction is that its effectiveness as a means of transferring angular momentum depends strongly on the distance. When the earth and moon are a distance r apart, the tides raised by either on the other have a height proportional to r^{-3}. The tidal torque which arises from the gravitational pull on the tides thus varies as r^{-6}. Clearly, the changes in the orbital elements take place rapidly when r is small and become negligible when r is large.

The frictional effects discussed above result from the relative rotation of the earth with respect to the moon. If the moon's angular velocity is greater than the component of the earth's rotation perpendicular to the orbital plane, the moon moves ahead of the lagging tidal bulge and angular momentum is transferred from the moon's orbital motion into the earth's rotation. If the component of the earth's angular velocity perpendicular to the orbital plane equals the angular velocity of the moon, then there are no frictional effects associated with the relative rotation of the earth and moon. Even in this case, there would be changes in the orbital elements, provided the moon moved in an eccentric orbit. The eccentric orbit gives rise to tides because of variation in the earth-moon distance. Because of friction, the tide on the earth is not high when the moon is closest to the earth, at perigee, but is high at some later time. Since the bulge is always along the line of centers, there is no relative rotation, and no angular momentum is transferred, but energy must be lost from the mechanical motion of the combined system because of friction. With relative rotation, there is still a radial component of the tide, and, with friction, this tidal component converts mechanical energy into thermal energy without transferring angular momentum.

The earth raises tides on the moon. The lunar tides supplement the frictional effects of the terrestrial tides. The moon's average angular velocity of rotation equals its orbital velocity, so that it presents a constant face to the earth. The major tides are those due to the eccentricity of the orbit; the tides, indicated schematically in Fig. 3 by the length of the arrows, are not high at perigee but are high at some later time. Since the tides are radial, no angular momentum is transferred, but there is a loss of mechanical energy from the earth-moon system (*3*).

Tidal interaction produces changes in both the energy and the angular momentum of the moon's orbit. These changes result in modifications of the semimajor axis of the orbit, a; of the inclination of the orbit to the ecliptic, I; and of the eccentricity of the orbit, e (*4*). I have already noted that, at present, the tides due to the relative rotation increase the angular momentum of the moon. Kepler's laws connect the increase in angular momentum with an increase in the semimajor axis, a. The long-term effect of the tangential component of the tides is to move the moon outward in its orbit. The radial tides associated with the eccentricity of the moon's orbit have the opposite effect. They remove energy from the orbit without changing the angular momentum, and, as a result, these effects alone tend to reduce a. At present, the tangential tides dominate the radial tides, and the moon is moving slowly outward. I have also noted that, because of the inclination of the orbital plane to the equator, the inclination of the moon's orbit and the obliquity of the equator change with time. The direction of the change is more difficult to establish, since it depends on the relative magnitudes of the torque acting about the x_2 and x_3 axes (see Fig. 2).

The effect of the frictionally retarded tides on the eccentricity can be understood by comparison of the magnitude of the forces at perigee and apogee. When the moon is at its nearest point, perigee, the force is greater than when it is at its farthest point, apogee. The effect of the force at perigee is such that the moon's distance at the next apogee is greater than it was at the preceding apogee. Similarly, the effect of the force at apogee is such as to increase the moon's distance at the next perigee, but, since the moon is farther removed at apogee, the force is less than the force at perigee. As a result, the orbit as a whole expands and becomes more eccentric at the same time. This effect is in part counteracted by the radial tides, which decrease the energy of the orbit and, in so doing, decrease the eccentricity.

So far we have considered only the earth and the moon. However, the sun also raises tides on the earth and the moon, and, if friction affects these tides, mechanical energy is removed from the combined energy of the earth-moon-sun system and angular momentum is transferred from the earth's rotational motion into the orbital motion of the combined earth-moon system about the sun. At present, these solar effects are a fraction (about one-fifth) of the lunar effects. The relative effectiveness of solar tides was less in the past, but will become dominant in the future.

Astronomical Evidence on Tidal Retardation

Early estimates of the effectiveness of tidal friction in slowing down the earth depended on reports of ancient eclipses. An identification of an eclipse yields past relative positions of the earth, moon, and sun. Munk and I have reviewed many of the ancient eclipse observations and have discussed the pitfalls one encounters in trying to draw, from an uncertain description of a heavenly event, conclusions about the celestial longitude of the moon (see *5*).

I now turn to the question of determining the moon's motion from astronomical observations made over the last 300 years. In principle, the problem is straightforward, since observation of the moon against a fixed background of stars determines the position of the moon in a celestial coordinate system. However, major difficulties arise because the observing platform, the earth, rotates at an irregular rate. Tidal friction causes a gradual slowing down of the earth. The earth's rotation, however, undergoes a wide variety of changes. Certain of these irregularities are attributable to motions in the atmosphere. For instance, the jet stream varies in intensity, and, because of this, the earth's rotation changes slightly. The tidal-friction problem is thus one of detecting a very low frequency signal against a background of noise, since the fluttering in rotation which is due to geophysical phenomena is much greater than the slow change resulting from the earth-moon-sun interaction.

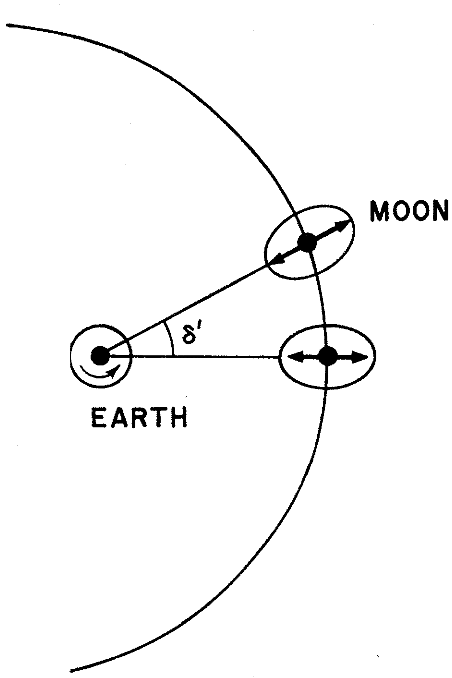


Fig. 3. Diagrammatic representation of the tides raised by the earth on the moon. The tides are due to the eccentricity of the moon's orbit. Because of friction, the tide is not high at perigee but is high later, at angle δ'.

Fortunately, there is a method by which the two kinds of changes can be disentangled. The interaction of the earth and moon affects both the earth's rotation and the motion of the moon. The irregular fluctuations in the length of day affect the observations of other planets, such as Mercury and Venus, but the tidal interaction between the earth and these other planets is so small as to have a negligible effect on their motion. We can, therefore, compare observations of the position of the moon with observations of Mercury, Venus, and the sun, and in this way remove irregularities in the earth's rotation that are due to geophysical phenomena from observations of the moon (*5, 6*).

The fluctuations in rotation can be described in terms of the discrepancy in mean longitude between the observed position of a body, such as the moon, and the position calculated on the basis of celestial mechanics; in this theory, the deformability of the planets and satellites is not taken into account. If variation in the rotation of the earth were the sole cause of the discrepancy, then the discrepancy in longitude would be proportional to the mean motion of the bodies as observed from the earth. Under this assumption, the discrepancies for the moon, sun, and Mercury, as plotted, should be the same. There is, in fact, a close resemblance in these discrepancies. However, the resemblance is not complete. There is a long-term drift between the discrepancies for the moon on the one hand and those for the sun and Mercury on the other. This long-term drift can be described in terms of the difference in discrepancy in longitudes weighted by the mean motions of the body. The weighted discrepancy difference is shown in Fig. 4 as a function of time; the weighted discrepancy depends on the orbital acceleration of the moon, since the effect of the earth's variable rotation has been removed. If the orbital acceleration were constant over time, then a parabola should fit the weighted discrepancy difference. Indeed, a parabola yields an excellent description of the astronomical observations (see Fig. 4).

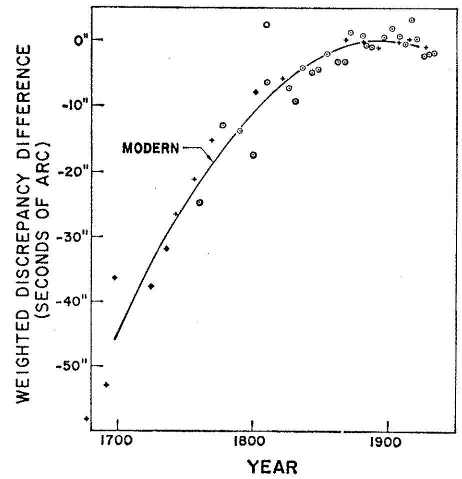


Fig. 4. Weighted discrepancy difference: ⊙, for the sun, +, for Mercury (unit = second of arc). The maximum in the curve results from setting the weighted discrepancy difference at zero for A.D. 1900.

The weighted discrepancy difference can be used to evaluate the torque exerted by the moon on the tidal bulge; the data shown in Fig. 4 yield a value for the torque of 3.9×10^{23} dyne-centimeters. In terms of the phase lag between the height of the tide and the line of centers of the earth and moon, this torque corresponds to a phase lag of 2.16 degrees, and the tidal torque is doing work at a rate of 2.5×10^{19} ergs per second.

In summary, modern astronomical observations yield a good estimate of the strength of the tidal interaction between the earth and moon. The strength of the interactions has remained constant over at least 300 years, and perhaps, if ancient eclipse observations are accepted, over 3000 years.

Numerical Calculations of Past and Future Conditions

Given the phase lag in the tide, there is a straightforward, though complex, pattern for calculating the past and future of the earth-moon system. In these calculations we require not only the present value of the phase

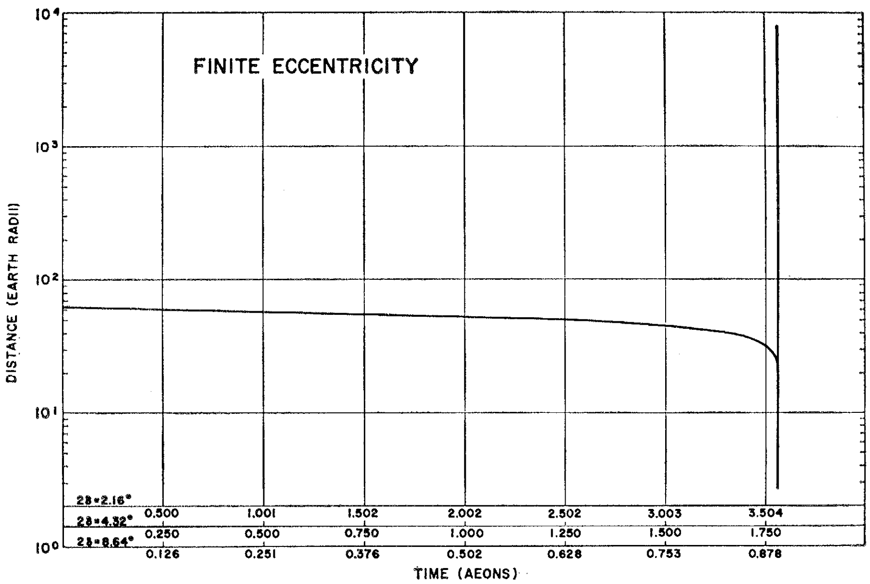


Fig. 5. The past variation in the earth-moon distance. The earth-moon distance is measured in present earth radii (1 earth radius ≐ 6371 km). The three time scales correspond to different assumptions regarding the phase lag of the tides raised by the moon and sun.

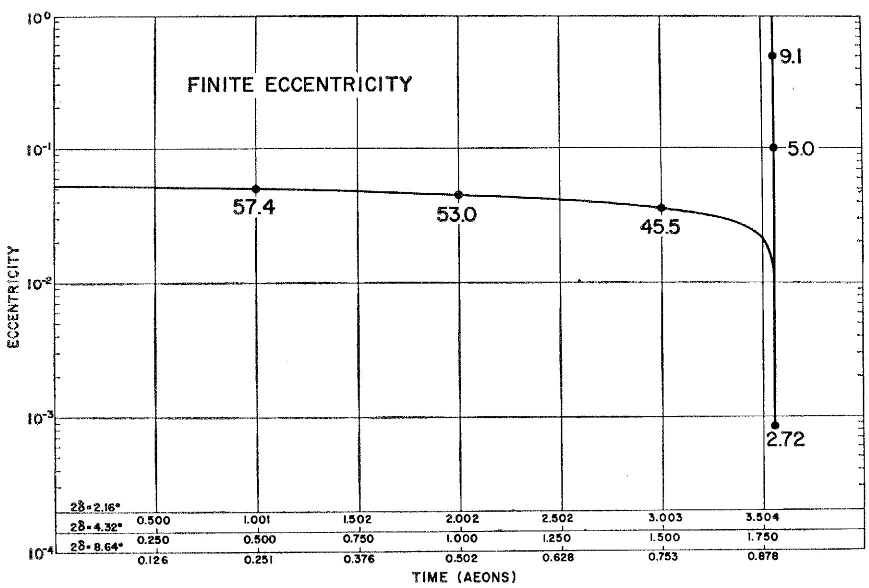


Fig. 6. The past variation in the eccentricity of the moon's orbit. Values adjoining the solid circles along the curve indicate the earth-moon distance measured in earth radii.

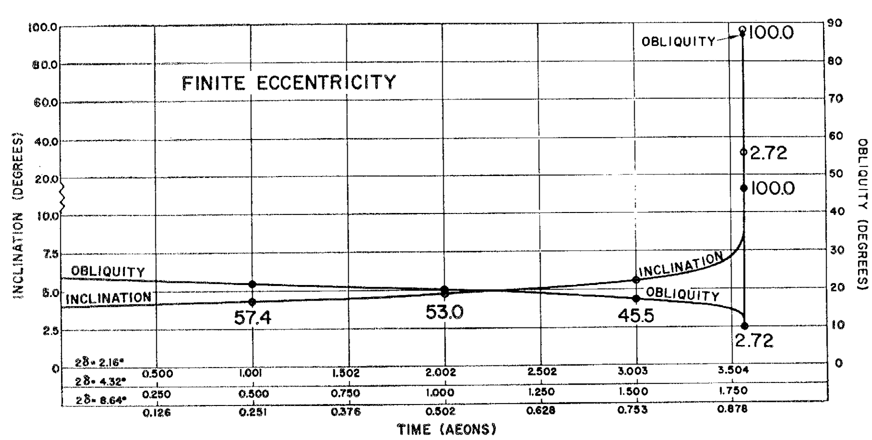


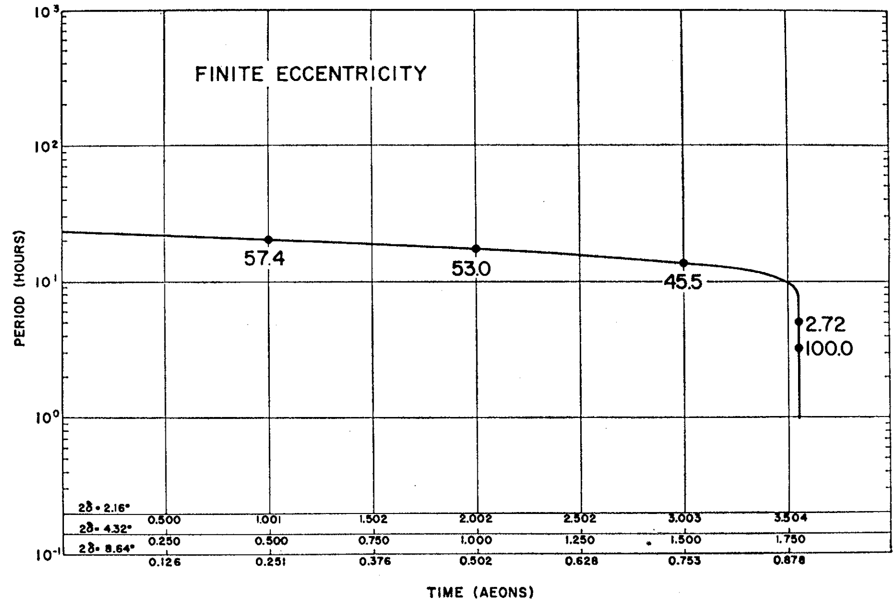
Fig. 7. The past variation in the inclination of the moon's orbit, and in the obliquity of the earth's equator, with respect to the ecliptic (values adjoining solid circles). Earth-moon distance (in earth radii) for the obliquity curve; (values adjoining open circles) earth-moon distance for the inclination curve.

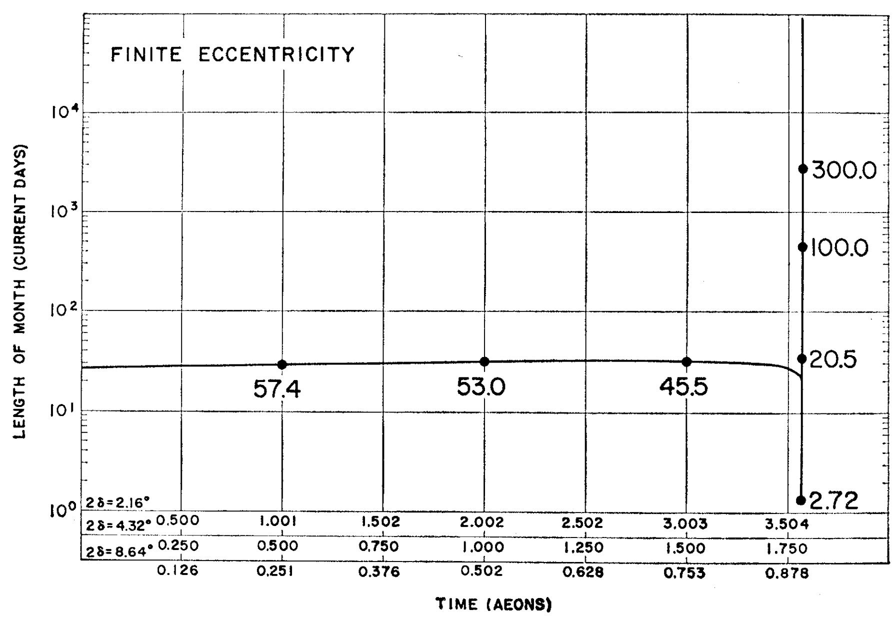
lag but an estimate of its variability during past times. On this point the evidence is uncertain, but I will assume that the phase lag has been constant in the past and will remain so in the future.

The history of the moon can be described in terms of the orbital elements connected with the energy and angular momentum of the orbit; these are the semimajor axis, a; the inclination of the orbit to the ecliptic, I; and the eccentricity, e. Accompanying changes in the orbital motion of the moon are changes in the rotational parameters of the earth. These are the magnitude of the angular velocity, Ω; the obliquity of the earth's equator to the ecliptic, γ; and the moment of inertia of the earth, C. The moment of inertia varies only slightly, and it is presumed that at all times the figure of the earth very closely approximates that of a rotating fluid having an internal density distribution identical to that of the present earth.

In calculating the variation of the orbital elements I have departed from Darwin's theory and have developed a theory in which the time derivatives of the orbital elements are expressed directly in terms of the forces due to the frictionally produced tidal potential (7). The theory requires no restrictive assumptions regarding the internal constitution of the earth and, further, takes into account the tides raised by the earth on the moon. The equations for the orbital elements are coupled to Euler's equations describing the changing earth's rotation. The coupled set of equations can be solved by means of numerical methods. In these calculations the effect of the solar tides has been taken into account.

The present value for the phase lag in the tides corresponds to a rate of increase of the semimajor axis of the moon's orbit of 3.2 centimeters per year. The increase in the semimajor axis with time is accentuated by the eccentricity. Because of the r^{-6} dependence of the tidal interaction, the tidal torque is increased more at perigee than it is decreased at apogee. As a result, the effect of the eccentricity on the tangential tides is to increase the semimajor axis. This effect is partly counteracted by the radial tides, which remove energy from the system but do not transfer angular momentum. At present, the rate of change of the semimajor axis is 1 percent greater than the rate of change would be for a circular orbit.





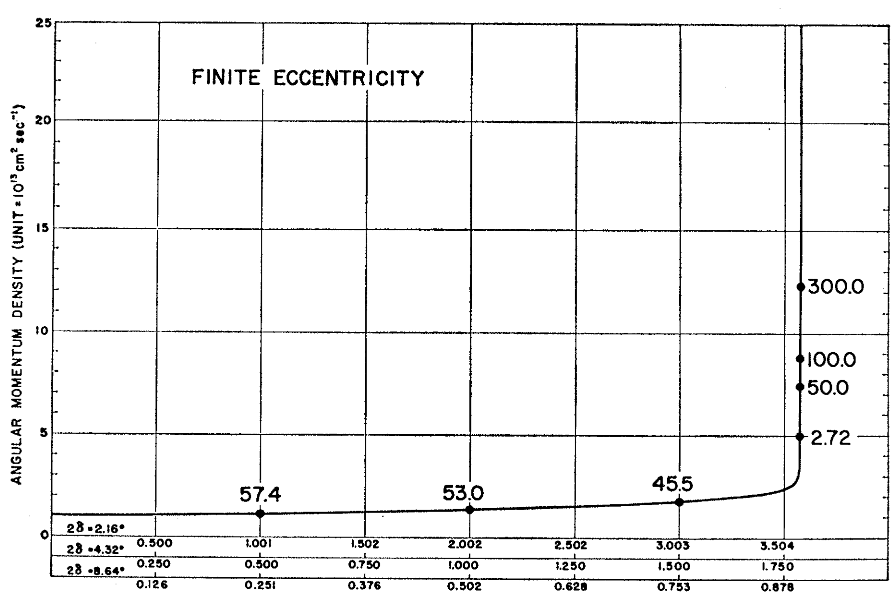


Fig. 8 (top). The past variation in the period of rotation of the earth; values adjoining the solid circles show the corresponding earth-moon distance (in earth radii). Fig. 9 (middle). Length of the sidereal month. The unit is the current day. Values adjoining the solid circles show the corresponding earth-moon distance (in earth radii). Fig. 10 (bottom). The past variation in the angular-momentum density associated with the earth's rotation. Values adjoining the solid circles show the corresponding earth-moon distance (in earth radii).

The past variation of the semimajor axis as a function of time is shown in Fig. 5. Figure 5 gives three time scales; the intermediate one, labeled $2\delta = 4.32°$, would be appropriate provided the phase lag remained constant at its present value. In this discussion I use the current value of the phase lag in fixing the time scale, though the time scales on the figures illustrate a range of possibilities.

The earth-moon distance reached a minimum 1.79 aeons ago (1 aeon = 10^9 years). Over the past aeon the moon has moved away from the earth at an almost constant rate. The rate at which the moon moved away was greater between 1 and 1.79 aeons ago and was at a maximum at the time of closest approach, since the rate of change of the semimajor axis depends on $a^{-11/2}$. Tracing the history back in time, we find that, after the close approach, the moon moves very rapidly away from the earth (see Fig. 5). This behavior can be understood only by examining the variation of the other orbital elements.

Figure 6 shows the variation of the eccentricity in past times; the past variability of the obliquity and inclination are illustrated in Fig. 7. At present, the eccentricity is increasing at a low rate: tidal interaction over 1 aeon increases the eccentricity by 12 percent. In past times, also, the eccentricity was increasing. However, at the time of the catastrophic approach, the moon's orbit became retrograde (that is, the moon moved in a direction opposite to the earth's rotation) (see Fig. 7), and, traced back in time, the eccentricity increases very rapidly. As the eccentricity increases, the semimajor axis of the moon increases without limit (see Fig. 5), while the perigee distance remains almost constant.

At present the inclination is decreasing at a rate of about 0.5 degree per aeon. In past times the rate of decrease was much greater, since the inclination varies with the semimajor axis as $a^{-13/2}$. Tracing back in time, we find that at the close approach the inclination increased rapidly, with the moon's orbit passing over the earth's axis of rotation. Accompanying the rapid changes in the inclination, the obliquity at first decreased and then increased, as Fig. 7 illustrates.

Figures 5–7 describe one possible course for the earth-moon system. According to this theory, the moon was captured, at 1.79 aeons ago, from a highly eccentric orbit of high inclination. For example, the initial earth-moon distance could have been 100 earth radii, at which time the moon would have had an inclination with respect to the ecliptic of nearly 90 degrees, while the obliquity would have been about 85 degrees. Because of the strong tidal interaction, the eccentricity would decrease at a rapid rate, as would the earth-moon distance and the inclination. The orbit becomes prograde (the moon revolves in the same direction as the earth rotates), the earth's axis becomes more nearly perpendicular to the ecliptic, and the moon moves out, with the eccentricity increasing and the inclination slowly decreasing.

Figures 8 and 9 illustrate proposed variations in the length of day and of the sidereal month; the month is measured in terms of the current length of day. Tracing the history back in time, we find the period decreasing slowly and then catastrophically as the moon plunges in toward the earth and then moves outward. The number of days in the month remains nearly constant until the time of catastrophic encounter, at which time it first decreases and then increases.

Figures 10 and 11 illustrate the proposed variability of two densities of great importance to a discussion of possible earth-moon histories. Accompanying the change in angular velocity, there is a variation, over time, of both the angular momentum per gram and the kinetic energy per gram. The variation in density of kinetic energy indicates the amount of rotational energy that must be dissipated within the earth if the moon follows the history illustrated in Figs. 5–9. The variation in density of kinetic energy can be compared with the thermal energy required to raise the temperature of a gram of silicates from 0° to a melting point of 1000°C; 1.67×10^{10} ergs per gram are required. Of this amount, the specific heat contributes 1.25×10^{10} ergs per gram, while the heat of fusion contributes the remaining 4.2×10^{9} ergs per gram.

Figures 12–15 illustrate the proposed future development of the earth-moon system, provided the phase lag remains constant. As the moon moves away, the effects of eccentricity, both on the tangential and on the radial forces, become progressively less. The maximum distance achieved after 4.9 $\times 10^{9}$ years is 72.7 present earth radii (see Fig. 12). The increasing obliquity decreases the effectiveness of the tangential forces. At the same time, the solar tides increase the period of rotation of the earth more rapidly than the lunar tides increase the period of the moon. The length of the month becomes shorter than the length of the day; the moon revolves more rapidly than the earth rotates, so the moon moves ahead of the lagging tide. These effects are accentuated by the radial tides, which remove energy from the orbit, decreasing the mean distance, without transferring angular momentum. The inclination of the orbit decreases monotonically, while the obliquity reaches a maximum at the maximum distance (see Fig. 13). In the final equilibrium state the moon is moving in the equatorial plane of the earth and the equatorial plane coincides with the ecliptic.

In the future there will be a gradual slowing down of the earth, an initial outward movement of the moon by a small amount, and then a return of the moon toward the earth, with the moon's inclination to the ecliptic gradually decreasing. The earth's obliquity with respect to the ecliptic will increase over the first 4.9 aeons, before decreasing at a more rapid rate to its equilibrium value.

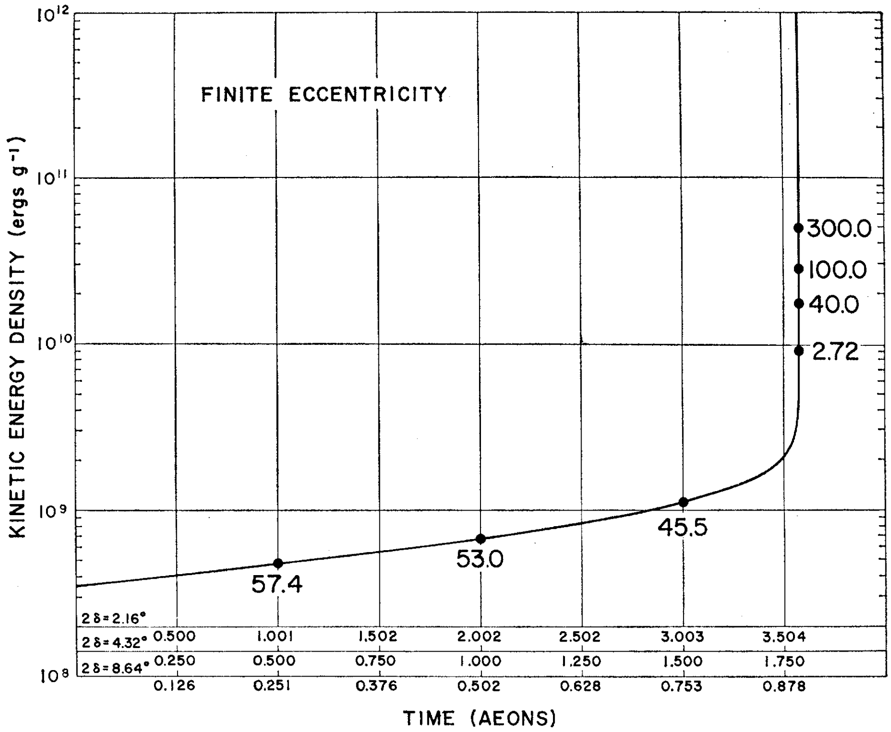
Initial Angular Velocity of the Earth

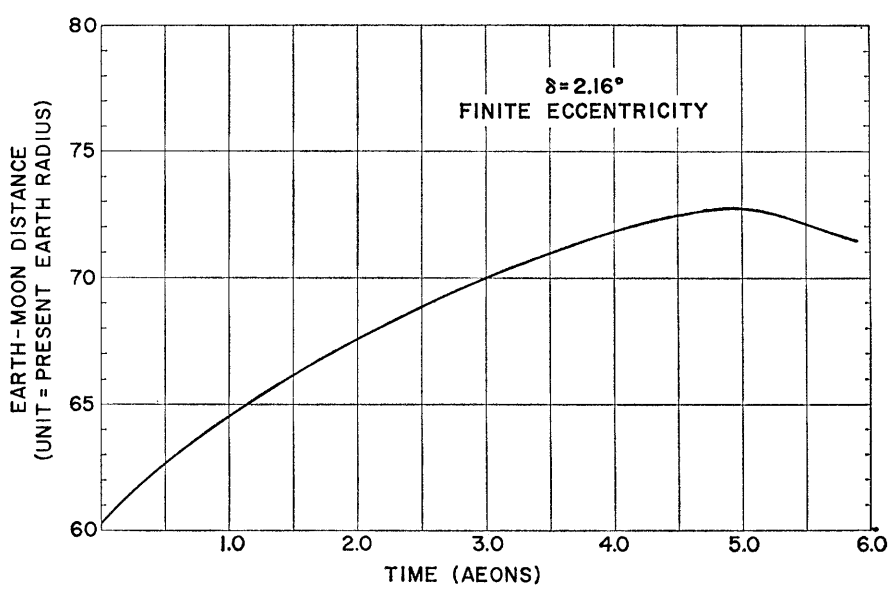
An understanding of the early development of the earth-moon system requires an estimate of the initial rotational period of the earth. Such an estimate may be derived either from a theory of planetary rotation or from an examination of the present rotation of the planets for evidence of initial conditions. Great difficulties attend the construction of a theory of planetary rotation. The angular momentum associated with the rotation of a planet is a small fraction of the angular momentum of its orbital motion. On general grounds we would expect that the rotational momentum must equal the difference between the initial orbital momentum of the matter that eventually forms a planet and the final orbital momentum about the sun. The planetary rotational angular momentum, therefore, is the difference between two large quantities, and the rotational momentum acquired by a planet must depend on the details of the accumulation process.

The alternative method, that of examining the planets for clues as to their initial angular momentum, is made more attractive by the fact that the rates of rotation of six of the planets are remarkably similar, despite major differences in orbital characteristics, masses, and moments of inertia (*8*).

The angular momentum of a planet can change through the action of tidal forces. Other processes that may have changed the rotational characteristics of planets have been suggested, such as interaction with the interplanetary plasma, or an interplanetary neutral gas, or dust. All of these processes at present are of minor importance as compared with tidal friction.

In examining the planets we note that the earth is, at present, losing angular momentum to the orbital motion of the moon. Furthermore, we should expect that both Venus and Mercury would have lost a substantial proportion of their angular momentum through tidal interaction with the sun. Indeed, the approximate equality of orbital and rotational angular velocities for Venus and Mercury can be understood in terms of a solar braking (*7*). Planets other than Venus, Mercury, and the earth should possess approximately their initial angular momentum. Mars is at too great a distance from the sun for solar tides to be effective, while its two satellites are too small in mass to produce any but a negligible change in the angular momentum. The major planets all have satellites. However, in their orbital motion these satellite bodies possess an angular momentum that is only a small fraction of the momentum of the planet. The large value for the ratio (mass of primary)/(mass of satellite) insures that only a small fraction of the rotational momentum can be transferred by tidal processes. Furthermore, the major planets are at such great distances from the sun that the solar tidal effects are completely negligible. We should, therefore, expect that the major planets, as well as Mars, would have a





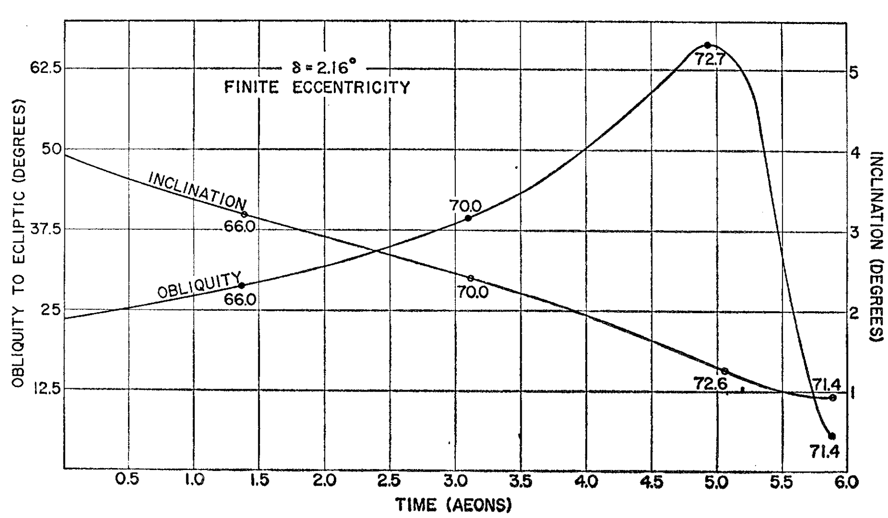


Fig. 11 (top). The past variation in the kinetic-energy density associated with the earth's rotation. Values adjoining the solid circles show the corresponding earth-moon distance (in earth radii). Fig. 12 (middle). The future variation of the earth-moon distance. The phase lag, 2δ, is set equal to 4.32 degrees. Fig. 13 (bottom). The future variation in the inclination of the moon's orbit, and in the obliquity of the earth's equator, with respect to the ecliptic (values adjoining open circles). Corresponding earth-moon distance (in earth radii) for the inclination curve; (values adjoining solid circles) corresponding earth-moon distance for the obliquity curve.

density of rotational angular momentum nearly equal to the initial density of angular momentum.

Figure 16 illustrates the dependence of the density of angular momentum on the mass of the planets. Venus and Mercury show a large deficiency of angular momentum as compared to the major planets and Mars. The earth also shows a deficiency, but less than that of either Venus or Mercury. The rotational momenta of the major planets and Mars are consistent with the hypothesis that there is a simple relationship between the rotational momentum and the mass of a planet. Indeed, I have argued that a relation between angular momentum and mass follows from dimensional considerations and is also consistent with an elementary picture of the mechanism of planetary formation (*7*, *9*).

Pluto and the asteroids do not follow the relationship shown in Fig. 16. The data on the rotation of Pluto are uncertain, but the rotational period may be about 6.4 days (*10*). Pluto thus has a deficiency of angular momentum relative to its mass. This may be due to the fact that it at one time was a satellite of Neptune and underwent tidal interactions. The high eccentricity of Pluto's orbit and the planet's unusual density argue for an abnormal history.

The asteroids show a wide range of rotational periods, and there is no way of estimating the rotational momentum of the primary body—if, indeed, there ever was a primary body. Furthermore, the asteroids may have exchanged angular momentum through close tidal interaction or through collision.

The empirical relation illustrated in Fig. 16 implies that the earth had an initial density of angular momentum of about 1.8×10^{13} cm^2 sec^{-1}. If the line had been drawn through Mars and Saturn, the two planets having the highest density of angular momentum for their mass, then the initial density of angular momentum of the earth should have been 2.4×10^{13} cm^2 sec^{-1}.

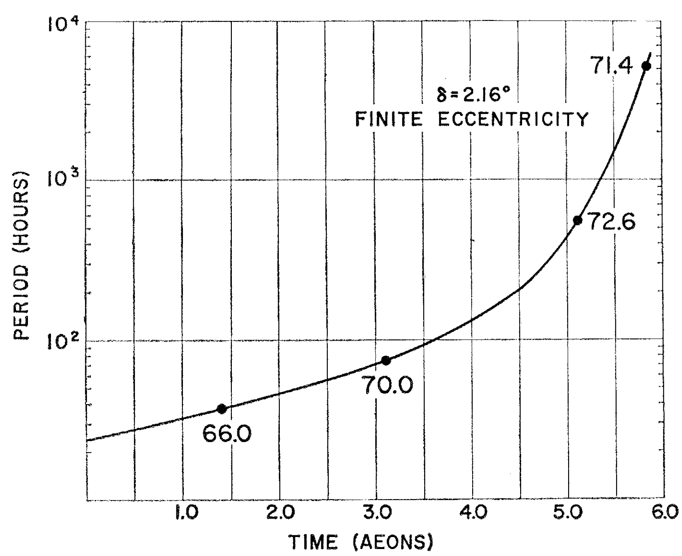
The low and high values for density of angular momentum correspond to rotational periods of 13.1 and 9.9 hours, respectively. I conclude that any theory for the history of the earth-moon system that requires an initial rotational period for the earth of much less than 10 hours must, at the same time, provide an explanation for the anomalously high initial density of rotational angular momentum of the earth. In terms of the history outlined in Figs. 5–11, the limiting values given above for initial density of angular momentum imply that the moon could never have been closer to the earth than about 40 earth radii, and thus they contradict the theory of close approach of a single satellite.

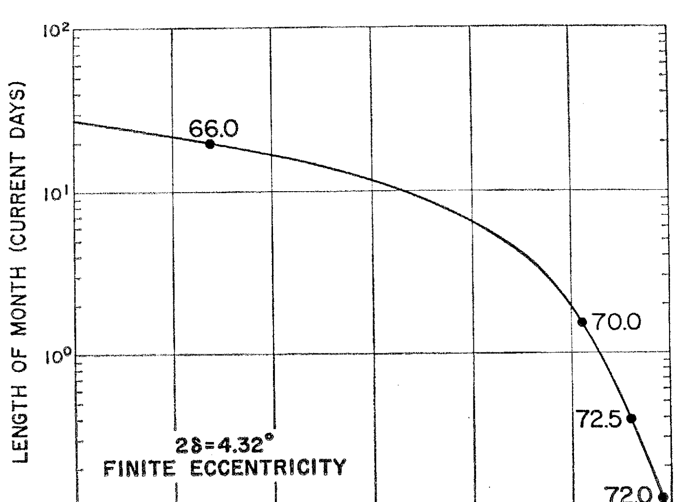
Origin of the Moon

Dynamical arguments limit theories of lunar origin in several respects. The present orbital elements of the moon and rotational parameters of the earth limit the possible initial conditions as well as their evolution, and, as we have seen, considerations of distribution of density of rotational angular momentum within the present solar system also limit possible initial conditions. Theories of the dynamical evolution of the earth-moon system which postulate a close passage of the two bodies imply dissipation of substantial amounts of energy within the earth. If this had occurred deep within the earth, then the long-term thermal history of the earth would have been disturbed, with consequences so far not observed.

Three general mechanisms have been proposed to explain the origin of the moon: origin as a binary system, fission of the earth to form a binary system, and capture. George Darwin's massive computations led him to suppose that the moon broke from the earth at an early stage and that tidal friction determined the present elements of the moon's orbit. Gerstenkorn has recently investigated the capture hypothesis, using the dynamical theory developed by Darwin (*11*). Aside from these two investigations, ideas regarding the origin of the moon have not been thoroughly probed from the dynamical point of view.

The fission theory of the origin of the moon is perhaps the best known of lunar theories. Darwin's initial suggestions have recently been extended by Wise and, independently, by Cameron, both of whom suppose that the earth became rotationally unstable as a result of a catastrophic change in the moment of inertia which accom-





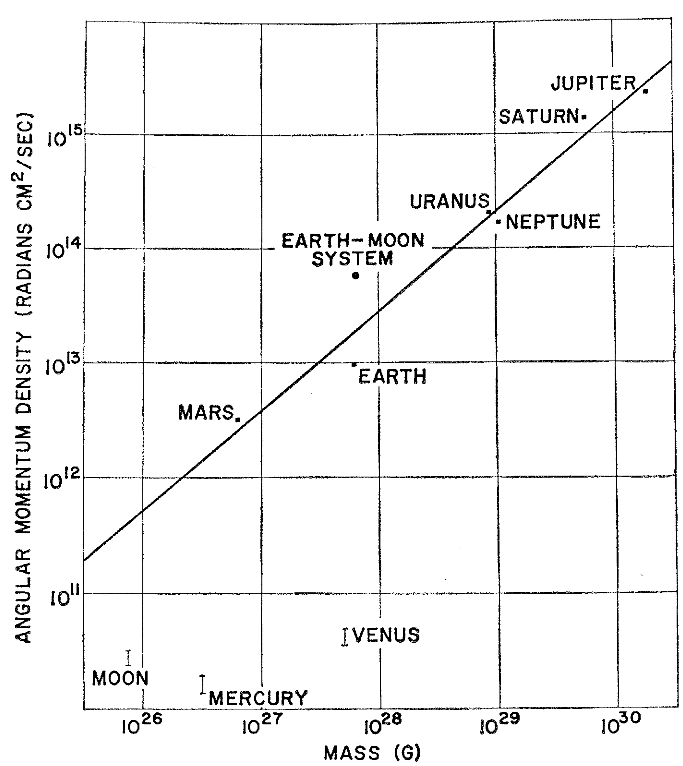


Fig. 14 (top left). Future variation in the earth's period of rotation. Values adjoining the solid circles show the corresponding earth-moon distance (in earth radii). Fig. 15 (bottom left). Future variation in the length of the month, with the current day as the unit. Values adjoining the solid circles show the corresponding earth-moon distance (in earth radii). Fig. 16 (above). The angular-momentum density associated with the rotation of the planets. The short vertical bars reflect the uncertainties in the angular velocities and moments of inertia of the moon, Venus, and Mercury. In determining the value for the present earth-moon system, the rotational momentum of the earth and moon and the orbital momentum of the moon about the earth were taken into account.

panied the formation of the earth's core (*12*). In these theories, the increased angular velocity results in the throwing off of either the moon as a whole or of small bits of matter which later accumulate to form the moon.

All versions of the fission theory require an initial density of rotational angular momentum in excess of that supposed to be representative of the initial solar system (see Fig. 16). In both the Wise and the Cameron theories, the initial density of angular momentum of the earth is greater than 2×10^{14} cm^2 sec^{-1}. The initial earth is thus required to possess a density of angular momentum about equal to that of Uranus, a planet which is more than ten times as massive as the earth.

The fission theories are also vulnerable on the basis of dynamical considerations. The rotational instability results in the throwing off of material from the earth in the equatorial plane. Once the material is in this plane, tidal interaction leads to no further changes in the inclination, and the obliquity remains constant. The present orbital elements of the moon cannot be accounted for. A further difficulty arises from the fact that the material ejected would, in general, have a higher angular velocity than the rotating body. Frictional forces would then be applied in such a direction that the material would be brought back toward the earth, and there would be no escape.

The binary-system theory proposes that the earth and moon accumulated from the same region of the initial solar cloud, the implication being that the bulk compositions of the two bodies are quite similar (*13*). The dynamical considerations reviewed above present difficulties for a binary-system theory only in the matter of time scale. In order to account for the evolution of an earth-moon system starting in a binary configuration, we must assume that the present rate of dissipation and the strength of tidal interaction are abnormally high. If the earth had an initial density of angular momentum of about 2×10^{13} cm^2 sec^{-1}, the inclination of the moon would have been 6 degrees, and the earth's obliquity, 18 degrees, with the earth rotating once every 11 hours. The initial eccentricity would have been about 3×10^{-2}, or slightly more than half the present eccentricity. With these initial conditions, the earth-moon system would have evolved under the action of lunar and solar tidal friction to its present configuration.

Urey has argued that the difference in density between the earth and moon implies that the moon accumulated elsewhere in the solar system and was then captured by the earth (*14*). The capture is presumed to have taken place during the early history of the solar system. The calculations discussed above clearly illustrate the difficulties one encounters in supposing that the moon was captured through tidal processes. Tidal capture would require an initial high density of angular momentum for the earth and the deposition of great amounts of energy within the earth (see Fig. 11). A multi-body interaction provides an alternative to the tidal-capture theory, but the details of such a process have not been explored. Urey's capture theory, like the binary-system theory, requires a time scale three times as long as that consistent with the present rate of acceleration of the moon.

Following a suggestion by Gold, I considered an alternative theory which circumvents the time-scale difficulty (*9*). The critical assumption is that initially the earth, like the major planets, possessed several moons. The rate of change of the orbital elements of a satellite depends on the force per unit mass of the satellite. The time scale for a given change in an orbital element varies inversely with the mass of the satellite. The rate of change of the torque acting on the earth varies as the square of the mass of the disturbing body: the height of the tide and the disturbing force that acts on the tide both depend linearly on the mass.

The time scale in the many-moon case is thus determined entirely by the mass of the most massive moon. It should be noted that the secular effects of the tidal bulge raised by one satellite on another are, on the average, zero. Thus, the total deceleration of the earth can be taken as the sum of the separate decelerations due to the various satellites. The time scale can thus be lengthened if the earth is supposed to have once possessed several moons —at least three or four. If the most massive moon were nearest to the earth it would move out the most rapidly and, in moving out, collide with the smaller outer moons and, in this way, form the present moon. The many-moon hypothesis permits a theoretical dynamical history consistent with the orbital-element, energy, and time-scale requirements.

The principal problem presented by the many-moon theory is that of describing a process by which the initial moons were captured, since, as Urey has pointed out, the density of the moon is evidence against a local accumulation of the primitive moons. While multi-body capture processes can be imagined for the major planets, no detailed calculations have been made concerning the capture of small moons by the earth.

The many-moon hypothesis, unlike other hypotheses of lunar origin, supposes that the surface of the moon is relatively young, having formed no more than about 1.5×10^9 years ago. The surface features would be the result of the final collapse of the collisional fragments into the moon.

Major Problems

There can be no question that, because of tidal friction, the length of the day was shorter in the past and will be longer in the future. Correspondingly, the obliquity of the earth's equator with respect to the ecliptic was less in the past than it is today, and it will increase in the future. The great problem is the time scale over which these changes take place. At present, astronomical evidence yields a time scale which is short as compared with the age of the earth. This short time scale, in turn, raises numerous problems, some of which I have discussed in considering the origin of the moon. Greater understanding of the subject will result from detailed identification of the mechanism by which the earth dissipated its rotational energy and from new methods for determining the length of the solar and lunar day in the past.

Wells has recently suggested that certain ridges in the skeletal structure of corals indicate the diurnal growth cycle (*15*). Seasonal fluctuations result in modulation of the diurnal cycle. Wells asserts that counts of the number of diurnal cycles per season give an estimate of the number of days per year. The number of days per year determines the length of the day, since the length of year remains constant. Fossil corals from the Middle Devonian show structure that can be interpreted as indicating that there were about 400 days per year. If this evidence is accepted, 350 million years ago the day would have been 21.9 hours long. An extrapolation based on the current value for the phase lag yields 21.7 hours for the length of day at that time. Wells's evidence provides a remarkable demonstration of the average constancy of the phase lag, if, indeed, the coral structures are indicators of the diurnal cycle.

Alterations of both the length of day and the obliquity of the earth are certain to have had major geologic consequences. Accompanying the change in the rate of rotation is a change in the figure of the earth; this alteration produces stresses within the earth and provides one source of energy for tectonic processes. Changes in obliquity and rate of rotation undoubtedly produce changes in the climate of the earth, the nature of which are still uncertain. The length of day determines, in part, the range of day-night temperatures. In the past, this range must have been smaller, and in the future it will be greater. The obliquity of the equator to the ecliptic is responsible for the different seasons, and it determines, in part, the temperature differences between the equator and the poles. If all other factors remain constant, a decrease in the obliquity results in a decrease in the seasonal variation and an increase in the temperature difference between pole and equator; these conditions held in the past. In the future, the increasing obliquity will increase the maximum difference between summer and winter and decrease the temperature difference between equator and poles. Increasing obliquity results in a more uniform distribution of insolation over the globe. Indeed, if the obliquity were about 35 degrees, then all latitudes would, on the average, receive approximately the same amount of solar energy. Provided insolation is the controlling factor, this obliquity would result in a subtropical climate over much of the world. The changes in the rotational parameter of the earth raise important questions regarding the climates of the past and the relation of these climates to the evolution of life on the earth.

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Plastids and Mitochondria: Inheritable Systems

Do plastids and mitochondria contain a chromosome which controls their multiplication and development?

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Two important types of cytoplasmic organelles are the plastids of plant cells, which function in photosynthesis, and the mitochondria of both plant and animal cells, which function in oxidative respiration. Within the last few years new information has become available which supports the hypothesis that these organelles do not arise *de novo* but that plastids arise from preexisting plastids and mitochondria arise from preexisting mitochondria. The original evidence reviewed by Granick (*1*) included observations on the division of plastids in algae and genetic studies of chloroplast inheritance in variegated plants and *Oenothera*. Recent studies indicate that (i) the plastids and mitochondria contain DNA and RNA; (ii) the organelles are self-duplicating bodies that do not arise *de novo*; (iii) the DNA represents a multigenic hereditary system which is not derived from the nucleus; (iv) the multigenic system of an organelle is responsible, in part, for the specific biochemical properties of the organelle; and (v) the organelles are controlled by an adaptive mechanism which in the case of plastids is responsive to light and in the case of mitochondria is responsive to O_2.

In this article we review the evidence for the foregoing statements. We consider especially the data provided by the genetic systems of the plastids of *Euglena* and the mitochondria of yeast. A comparison of the properties of these two genetic systems illustrates their fundamental similarities (Table 1). For reasons not known, these systems are exceptionally mutable, a property, however, which has made possible the recognition of their multigenic components.

Evidence for Nucleic Acids in Plastids

In order to establish that plastids are semiautonomous units with their own hereditary apparatus, it is necessary to show that (i) they contain DNA and RNA; (ii) the DNA replicates in the organelle; (iii) the DNA functions to make messenger RNA; and (iv) the messenger RNA codes specifically for certain proteins or enzymes of the organelle.

Experiments to test for these properties are of various kinds, and some of the tests are more conclusive than others. However, taken together, the data strongly support the view that these organelles contain an autonomous DNA genetic apparatus.

DNA content. Reported findings of

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