4 July 1969, Volume 165, Number 3888

SCIENCE

Two Alternatives for the History of the Moon

Analysis of the moon's surface might provide the key to the early history of the earth.

H. Alfvén and G. Arrhenius

The theory of Gerstenkorn (*1*) and its further development (*2–5*) have made it probable that the moon was originally an independent planet which was captured by the earth and brought into the present orbit by tidal action through geological time (*6–8*). According to Gerstenkorn's original calculations the moon was captured in a wide retrograde orbit (perigee 26 $R_\oplus$) making an angle of about 150° with the earth's equatorial plane. After criticism by Goldreich (*9*) Gerstenkorn has revised his calculation. Varying the assumptions about the dissipation in the moon, he arrives at capture orbits which all have a very small perigee ($< 3\ R_\oplus$), and an inclination of about 90°, in some cases even smaller. Such orbits are similar to Singer's case (in which the moon is restricted to movement in the equatorial plane of the earth). In Gerstenkorn's calculations the lunar orbit develops in such a way that the moon is brought to the Roche limit ($R = 2.9\ R_\oplus$) or even inside it. The consequences of such a close approach would be catastrophic. Although the moon would spend only a short time (about 100 to 1000 years) close to the Roche limit, it would, during this time, supposedly produce tidal waves up to 6 km high. The tidal friction would result in considerable heating of the earth as well as of the moon. Moreover, if the moon were to penetrate the Roche limit, it might break up and eject fragments into space (*8*). In the following sections we consider some phenomena associated with a catastrophic event.

It may turn out that some of the consequences of such a development are irreconcilable with geological evidence. If this should be the case one may ask whether the moon's postnatal evolution could have been more gentle, without catastrophic events of this magnitude. We show that in a moon-earth approach a number of secondary effects may have been important which previously have not been taken into account, and which indeed result in a protracted orbital evolution with drastically diminished rate of tidal dissipation.

Our present knowledge appears insufficient for us to choose between the catastrophic and the noncatastrophic alternatives. In the last section below we discuss what new empirical data would enable us to make such a choice.

Dr. Alfvén is professor at the Royal Institute of Technology, Stockholm, Sweden, and visiting professor at the Department of Applied Physics and Information Science, University of California, San Diego. Dr. Arrhenius is professor at Scripps Institution of Oceanography, University of California, San Diego.

The Catastrophic Alternative; Effects on the Earth

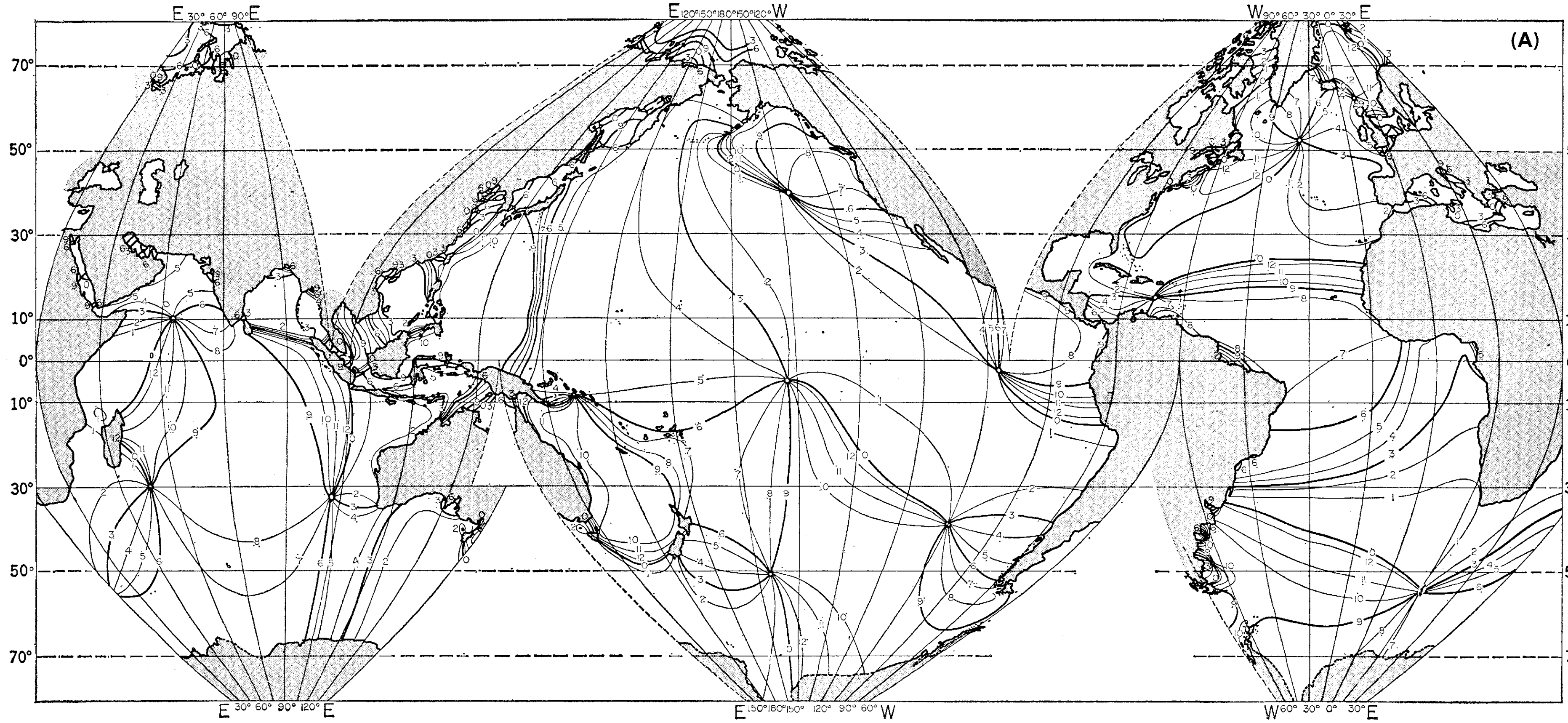
According to Gerstenkorn (*1, 5*) and MacDonald (*2*) the approach of the moon to the Roche limit would brake the rotation of the earth and cause release of large quantities of rotational energy during about 100 to 1000 years. Several attempts have been made to identify the lunar approach in the geological record on the basis of the pronounced tidal effects (*10–12*); this interpretation has been criticized by Cloud (*13, 14*). In the identification attempts quoted, the Late Precambrian, about − 0.7 eon, is suggested as the time of tidal culmination. Gerstenkorn estimates the age of the close approach at about −2 eons; however, this extrapolation has an uncertainty of at least a factor of 2.

Gerstenkorn and MacDonald base their models on tidal friction in the solid earth as the dominant mode of rotational braking. Munk (*15*), however, suggests that this effect is negligible compared to energy dissipation by ocean tides; in this case the proposed braking releases energy at a rate high enough to evaporate the ocean and to heat the atmosphere and the surface of the earth far above 100°C. This would in all likelihood have destroyed any life existing at the time. Such a consequence is not acceptable, for there is no evidence that biological evolution was interrupted.

These arguments, however, do not necessarily nullify the identification attempts because the tidal theory taken as a basis of the celestial mechanics calculations is an oversimplification. According to this theory the tidal amplitude would be

$$f = 147\ (R_\oplus/R)^3 \text{km} \qquad (1)$$

where $R_\oplus$ is the earth's radius and R the distance of the moon. It is the gravitational action between this bulge and the moon which produces the braking. For an approach to the Roche limit ($R = 2.9\ R_\oplus$) we find a tidal amplitude of $f = 6.1$ km. Present con-



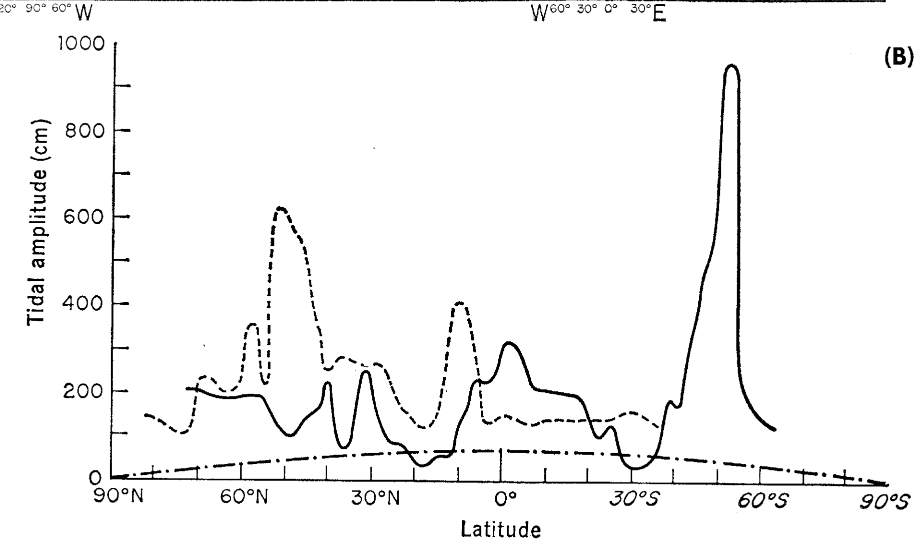


Fig. 1. (A) Phase relations of tides in the world ocean. The map shows the cotidal lines of the semidiurnal tide referred to the culmination of the moon in Greenwich. The tidal amplitude approaches zero where the cotidal lines run together into amphidromic centers, and on nodal lines where the cotidal lines run parallel (such as between Japan and New Guinea). Much of the tidal motion thus has the character of rotary waves; among the exceptions is the south and equatorial Atlantic Ocean where the tide mainly takes the form of north-south oscillation on east-west nodal lines (*39*). This complex reality should be compared to the simple concept which is basic for existing calculations of the lunar orbital evolution and which pictures the tide as a sinusoidal wave progressing around the earth in the easterly direction (dot and dashed curve in Fig. 1B) (from *39*). (B) Tidal amplitude on the Atlantic coasts as an example of the actual amplitude distribution in comparison with the simple Laplacian tide concept. The curves show the average range at spring tide of the semidiurnal tide as a function of latitude. In comparison with the (much less known) open ocean amplitudes, the coastal amplitudes are increased by cooscillation with the oceanic regions over the continental shelves. The distribution illustrates further the fact that tidal dissipation is governed by a series of complex local phenomena (see, for example, *15*) depending on the configuration of continents, shelves, and ocean basins and that the theoretical Laplacian tide obviously cannot serve even as a first-order approximation (from *39*). Solid curve, western side of Atlantic Ocean; dashed curve, eastern side of Atlantic Ocean; dot and dashed curve, Laplacian tide.

ditions ($R = 60\ R_\oplus$) give $f = 67$ cm.

Actual observation of the present ocean tides show that this simple theory is not at all applicable. Instead of a worldwide double sine variation of the predicted amplitude, the tides are extremely irregular (Fig. 1, A and B) with amplitudes which, in some regions, are larger by more than a factor of ten and, in other regions, approach zero. The phase lag could have any value because the structure of the earth differs drastically from that of a homogeneous fluid body. Since the simple tidal theory does not give even a first-order approximation of reality under present conditions, it is not legitimate to use Eq. 1 in order to extrapolate the tidal braking to the conditions at the close approach.

In yet another respect we are far from the idealized case. To illustrate this, let us consider the geographical motion of the sublunar point (the intersection of the vector from the center of the earth to the moon with the earth's surface) at a time near the close approach. According to a simple theorem of spherical geometry, the latitude ϕ and the longitude λ_M of the moon are given by

$$\sin \phi = \sin i \cos \omega\ (t - t_0)$$

$$\tan \lambda_M = \frac{1}{\cos i} \tan \omega\ (t - t_0)$$

where i is the inclination of the moon's orbit (referred to the earth's equatorial plane), ω is the angular velocity of the moon, assumed to move in a circular orbit, and t_0 the time of its maximum latitude. As the earth spins, with the velocity Ω, the geographical longitude is

$$\lambda = \lambda_M - \Omega t$$

We apply this to the case where the moon is moving in a highly inclined orbit ($i = 70°$) with a period seven times the earth's spin period (corresponding to a lunar distance of about 9 $R_\oplus$). Figure 2 shows the geographical motion of the sublunar point in this case.

If the earth were covered by a uniform layer of water, the moon would produce a tidal bulge with one apex in the sublunar point and another on the opposite side. These bulges would for a few hours move with high linear speed in the equatorial region and then move toward the poles. They would remain at high latitudes for a considerable fraction of the 7-day month, moving with comparatively low linear velocity and then speed up while returning to the equator and crossing into the opposite hemisphere. The water would be pumped from the equator toward the poles and would later return to the equator where the tidal wave would proceed at a velocity of 2 to 3 km/sec.

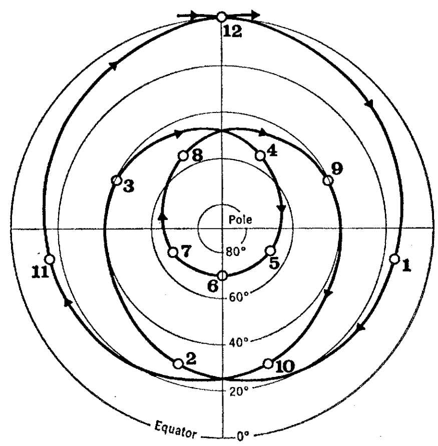


Fig. 2. Motion of the sublunar point in the northern hemisphere. The moon is assumed to orbit with a period seven times the earth's spin period in a plane with an inclination of 70°; this corresponds to conditions at a time not very distant from the close approach. The boldface figures mark consecutive positions of the sublunar point, each interval corresponding to 15° motion of the moon. The figure illustrates another principal deviation from the simple theory, resulting in nonlinear tidal dissipation.

Although this simplified picture in principle illustrates the nonideality under consideration, it is certainly also unrealistic because the finite depth of the ocean produces nonlinear phenomena. Furthermore, the presence of continents changes the situation drastically. Paleomagnetic investigations (see, for example, review in *16*) indicate that the present continental masses were gathered into two supercontinents in Late Paleozoic time, centered in high latitudes, one in the Southern, the other in the Northern Hemisphere. Such a concentration of continents in high latitudes is indeed a main result of the primordial segregation of the earth's crust in the physical model proposed by Elsasser (*17*). Consequently, it is reasonable to assume that the paleomagnetically observed distribution of continents in the upper Paleozoic may extend back in time to the earlier stages of the earth's history which have not yet been extensively explored.

With the high latitudes occupied by land masses and small epicontinental seas it is conceivable that practically no tidal flooding would occur in these regions. High tidal waves and release of energy at braking of the earth's rotation would then be concentrated in the equatorial zone. Our present geological record is derived from the continental and epicontinental areas, and consequently only peripheral effects of the tidal flow would be found. Furthermore, the rate of dissipation of energy under these conditions may be orders of magnitude lower than that predicted by the simple theory. If the moon moves in a highly elliptic orbit (*4, 18*) during the close approach to the earth, a still more complicated pattern would arise, but the above conclusions remain essentially the same.

As shown by our simplified example, we cannot exclude compatibility of a close approach with the observed geological record until we have a more detailed knowledge of the distribution of oceans and continents at the time. In the absence of this knowledge, and, therefore, of the actual dissipation rate, we cannot estimate the time of closest approach from celestial-mechanical extrapolations.

Aside from this uncertainty it has been suggested (*19*) that the catastrophic alternative, if occurring at all, must be relegated to the earliest phase of the history of the earth. The argument invoked is that if a large number of fragments left the moon they would preferentially impact on the earth and obliterate the sedimentary record existing at the time; because patches of sediments as old as 3 eons are observed (*20*) this would place a lower limit on the age of a major bombardment of the earth. However, as will be discussed further below, it is possible that the trajectories of the ejecta largely preclude these from falling on the earth. Furthermore, most Precambrian sediments have been obliterated, truncated, or metamorphosed; the small areas that are actually visible in outcrop are obviously such as have escaped damage by erosive agents, including impacting fragments. Finally, a number of impact events were of such magnitude that their effect extends into the now exposed crystalline basement rock. Although the age can be fixed only within limits of several hundred million years in most of these cases (*21*), the majority of them encompass the Late Precambrian within these limits. The Vredefort dome and most of the Canadian craters fall in this category. This is the case also for a number of other cryptovolcanic structures, considered, but not proven, to result from impact.

We do not wish to invoke these arguments in direct support of the notion that material was ejected from the moon late in the history of the solar system; however, it does not appear that such an assumption at the present time may be rejected on the basis of geological evidence.

The Catastrophic Alternative; Effects on the Moon

The main effects produced on the moon would include heating and, if the moon came inside the Roche limit, a partial disruption. The latter effect would influence the evolution of the lunar orbit.

If the moon were captured in an orbit with a large perigee—as in Gerstenkorn's first version—the heating would be essentially due to the braking of its initial rotation. The effect suggested is relatively small, but, because the heat may be dissipated preferentially in loose material at the surface, we cannot exclude melting of a surface layer.

If on the other hand the moon were captured in an orbit with the perigee close to the Roche limit—as in Gerstenkorn's revised version (and also in Singer's model)—a fraction of its orbital energy would be converted into heat. According to Gerstenkorn the heat, if distributed uniformly over the whole volume of the moon, would raise its temperature to about 1000°C. As it is likely that most of the heating would occur in a surface layer, this could be melted, but not necessarily the interior. Because the melting, and also the subsequent solidification by radiative cooling, takes place when the moon is close to the earth and hence is elongated by tidal action, this process could possibly cause the present deformation of the moon.

If the moon comes inside the Roche limit, a tidal break-up may take place in the strongly inhomogeneous gravitational field. Regardless of whether the moon were fractured or not, fragments from the surface would be ejected from the apices of both the inner and outer tidal bulge. In Gerstenkorn's second model, the moon moves for a time in a highly elongated ellipse with its perigee inside the Roche limit (Fig. 3). The fragments ejected from the inner tidal bulge will move in elongated orbits within the lunar orbit. Through the precession of orbits, the fragments have a large probability of being recaptured by the moon. In principle none of these ejecta would be intercepted by the earth. However, after being scattered out of their orbits by collision some of them may be captured, but they need not necessarily be uniformly distributed over the earth's surface; under certain conditions most fragments would hit the equatorial region.

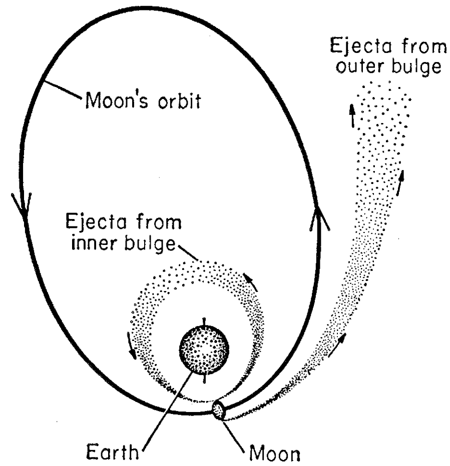


Fig. 3. Catastrophic alternative; breakup of the moon at the Roche limit. Soon after its capture by the earth the lunar orbit transgresses the Roche limit; this leads to deformation and fracturing of the moon. Fragments from the inner bulge are ejected into *cis*-lunar space. Most of them are ultimately recollected by the moon and produce lunar craters at impact. Fragments from the outer bulge are thrown out in interplanetary space; some of this material may be stored in resonance orbits near the earth's orbit. Collision scattering out of this reservoir provides new fragments, some of which are eventually captured by the earth as meteorites.

The fragments ejected from the outer bulge (Fig. 3) would move outside the moon's orbit in still more elongated ellipses, or in parabolic or hyperbolic orbits. Some of them would be swept up by the moon during its later recession from the earth; some would leave the earth's gravitational field and orbit around the sun.

The Catastrophic Alternative; Origin of Meteorites

Time-dependent phenomena in meteorites include the accumulation of spallation products due to cosmic ray bombardment and the accumulation of decay products of radioactive elements. The dosage of cosmic rays can be used to estimate the length of exposure (exposure age) of the meteorites as small bodies (with dimensions less than the order of a few meters) in free space. The amount of stable decay products from radioactive disintegration, such as He^4 and Ar^{40}, relative to their parent elements, defines the time elapsed since the solid formed, provided that no later gas removal (for example, by heating) has taken place. In the case of such a disturbance the age obtained from gaseous decay products such as helium and argon (degassing age) is less than the original formation age indicated by solid decay products such as Sr^{87}. These relationships have been extensively studied in meteorites; the results can be summarized as follows: The formation ages are uniformly high and of the order of 4.5 eons. One interesting exception, the iron meteorite Kodaikanal, with an age of 3.8×10^9 years has been reported (*22*). The degassing ages mostly coincide with the formation ages, particularly when precautions are taken to exclude materials with inferior gas retentivity. A notable exception is the group of hypersthene chondrites (Fig. 4), all 49 of which (*23*) were found to have undergone extensive degassing 0.5 to 0.7 eon ago, the range indicating the uncertainty of the analysis.

The cosmic-ray exposure ages differ markedly between iron meteorites and stones. The latter consistently have low exposure ages, apparently representing a few breakup events distributed over the last 0.1 eon period—this includes also the hypersthene chondrites mentioned above; they consequently appear to have been degassed (apparently by shock heating) while they were still part of a larger parent mass which was broken up into meteorite bodies at a much later time, dated by the exposure age.

In contrast, the exposure ages of the iron meteorites show a wide range, from the order 0.01 to 1.0 eon. A remarkably coherent distribution (Fig. 4) is shown by a large and distinct group of octahedrites which all bear evidence of shock and which were exposed about 0.7 eon ago (*24, 25*).

Jaeger and Lipschutz have suggested (*25*, p. 1826) together with Heymann (*23*) that the degassing age of 0.5 eon originally assigned to the hypersthene chondrites has an attending experimental uncertainty large enough to permit and suggest that this shock event is identical with the one leading to the exposure of the iron meteorite group 0.7 eon ago—they propose this event to be a collision between two asteroids. The coincidence in time between this event on one hand and the time of close approach suggested by Olson on the other makes it tempting to suggest that ejection of lunar material occurred as a consequence of the earth-moon interaction during the close approach, and that the meteorite group referred to and possibly also other less-distinctively labeled meteorites represent the remainder of these ejecta. The mechanism for subsequent orbital storage of these fragments is discussed below.

A striking fact which must be explained regardless of which origin is claimed for the meteorites is the relatively large size of the stone meteorite parent bodies generated at the shock-degassing event compared to the size of one or a few meters of the iron meteorites presumably generated in the same event. A likely explanation is provided by the concept (*26*) that space erosion more seriously affects the brittle and friable silicate bodies than metallic objects. The fine silicate debris generated at the 0.7 eon event would consequently have disintegrated to dust and small fragments, not immediately recognizable as extraterrestrial, and consequently not recovered as meteorites. By this comminution, large boulders would suffer a smaller fractional change by erosion and would be strongly favored in the ensuing modified size distribution. It appears possible that iron meteorites in the primitive moon prevailed in roughly their present size dispersed through the silicate material, and that the break-up liberated them without extensive change in size. Such a distribution of iron in the silicate has also been suggested for other reasons (*27*).

Öpik (*28*) and Arnold (*29*) have calculated the collision cross section of the earth for meteorites moving near the earth's orbit, and they found that the lifetime of meteorites crossing this orbit is of the order of 0.01 eon. If we accept their results the meteorites could not originate from the Gerstenkorn event, since this would require storage in interplanetary space for 0.7 eon. In principle they could be stored in the outermost region of the earth's gravitational field, but this possibility is excluded (*28*) because they impinge on the earth with velocities exceeding the escape velocity.

However, Öpik and Arnold base their theory on the assumption that the approach of meteorites to the vicinity of the earth is a random process; this treatment consequently does not take into account resonance effects. Such effects are in many cases known to prevent bodies from being captured by a planet even if they are orbiting at the same distance from the sun. One example is the Trojans, which are captured in the two libration points +60° and −60°, preceding or following Jupiter. Their average distance from the sun equals that of Jupiter. They move around the libration points, some of the bodies oscillating with large amplitudes. Their motion is stable in the sense that they would never be captured by Jupiter, unless their motion were strongly disturbed. Another example is the resonance relationship of Pluto to Neptune (*30*).

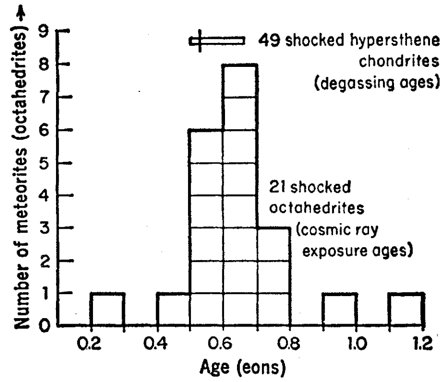


Fig. 4. Frequency distribution of cosmic ray exposure ages of shocked octahedrites (*25*), and degassing ages of shocked hypersthene chondrites (*23*). The maximum at 0.6 to 0.7 eon may reflect a single event.

There are also other storage possibilities. For example the Hilda asteroids have a period which is two-thirds that of Jupiter. A resonance with Jupiter prevents them from colliding with this planet even though some of them intersect Jupiter's orbit (see, for example, *31*). In principle every integral-fraction resonance gives a similar possibility.

In conclusion the possibility cannot be neglected that a reservoir of bodies, capable of yielding meteorites, can be maintained in interplanetary space for a considerable time, either at the earth's libration points, or in other resonance orbits near the earth's orbit. Because such orbits could have large eccentricities and inclinations, these bodies might intersect the earth's orbit with velocities relative to the earth which are a considerable fraction of the earth's orbital velocity. If their motion were disturbed enough to liberate them from the resonance capture they would impact on earth as meteorites with a velocity considerably in excess of the terrestrial escape velocity.

The scattering out of resonance orbit may in the case of meteorites be due mainly to collision. Such collisions must under any circumstances be assumed in view of the exposure age evidence referred to above which confirms that the silicate bodies, formed at the original shock event, were further broken up into meter-size fragments in relatively recent time.

The Noncatastrophic Alternative

In the absence of decisive observational confirmation of the catastrophe discussed above, a protracted evolution of the lunar orbit is another realistic consideration. In this alternative a spin-orbit resonance prevents the moon from ever coming very close to the earth.

During the last few years resonance phenomena in the solar system have attracted much interest; an important result has been the discovery that both Mercury and Venus are captured in spin-orbit resonances (*32*). Allan (*33*) has discussed a related type of coupling, namely between the spin of a central body with longitudinal inhomogeneity and a satellite orbiting around it. If the orbital period of the satellite equals the spin period of its central body, it is obvious that a longitudinal inhomogeneity will cause a force with a component parallel to the orbital velocity of the satellite. The result is a locking of the satellite motion, so that the period is exactly the same as the spin period of the central body; the phase is determined by the position of the longitudinal inhomogeneity. Such a resonance takes place even if the satellite moves in a circle in the equatorial plane. The change of the moon's orbit due to tides can be classified as a resonance of this type. The longitudinal inhomogeneity of the earth in that case consists of the idealized tidal bulges, which by definition always rotate with the same angular velocity as the moon.

There are also higher-order resonances. If the period of the satellite is α/β times the spin period (where α and β are integers), a similar resonance is produced, but only if the inclination and eccentricity of the orbit (or both) exceed certain values. If $\alpha \neq 1$, $\beta \neq 1$, no resonance is possible for the special case of a satellite in a circular orbit in the equatorial plane.

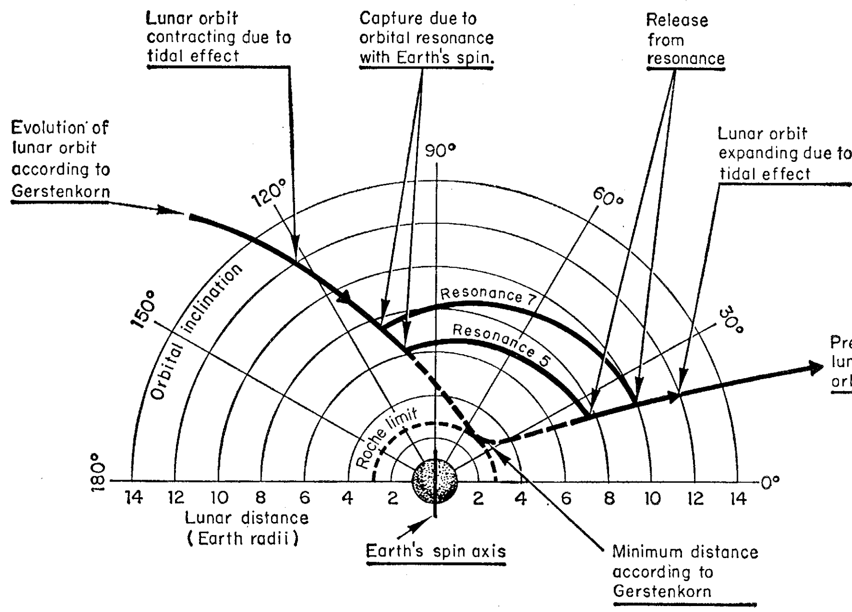


Fig. 5. Noncatastrophic alternative; spin-orbit resonance prevents the moon from reaching the Roche limit. The retrograde lunar capture orbit contracts due to tidal dissipation, until resonance between the lunar orbit period and the spin period of the earth locks the moon in a slowly expanding orbit. Since the moon never comes very close, no breakup or autoejection occurs and the tides do not reach catastrophic heights. When the orbital inclination has decreased below a critical angle (suggested in the diagram at about 25°), the resonance locking is broken and the moon recedes to its present orbit at 60 $R_{\oplus}$.

Our lack of knowledge of the distribution of gravity anomalies at the time in question makes it impossible to decide in what way the conditions for a spin-orbit coupling of the moon were satisfied during the evolution of the lunar orbit. We can state, however, that at least as long as the moon is not too close to the earth, mountains comparable to or larger than the tidal bulges are likely to exist. Hence, resonances of the Allan type may well change the tidal evolution of the lunar orbit. For higher resonances the mass of the mountains must be several times larger than that of the tidal bulges.

Another longitudinal asymmetry may act similarly. The geographical location of seas and continents will cause the size and phase lag of the tidal bulge to vary when it proceeds around the earth as illustrated in principle in Fig. 1, A and B. The result is that the attraction of the tidal bulge on the moon will vary periodically; this effect may also contribute to a resonance capture. Nonlinearites of some kind are actually indicated by irregularities in the change of length of the synodic month during the recession of the moon from its position during Late Cambrian to its present position (*34*).

If resonance effects played a significant role in the lunar orbital evolution, calculations of the Gerstenkorn type do not allow us to reconstruct with certainty the capture orbit of the moon. However, we may approach this problem in an independent way. In the planetary system there are six satellites in retrograde orbits—Jupiter VIII, IX, XI, XII, the Saturnian satellite Phoebe, and the Neptunian satellite Triton. Of these only Triton is large enough to cause tides which change its orbit. The orbits of the other five have certainly not been perceptibly changed by tidal action. From this we may conclude that a cosmogonic capture mechanism must exist which is capable of bringing satellites into retrograde orbits. The inclinations of Jupiter VIII, IX, XI, XII, and Phoebe are all between 147° and 164°. It is possible that Triton has reached its present orbit after tidal evolution from a similar orbit (*35*). Hence it is reasonable to suggest that the moon also could have had an analogous evolution. By coincidence a satellite orbit of this type is similar to the orbit in which the moon moved shortly after its capture according to Gerstenkorn's first paper. Hence we can use his calculations for the first phase of the evolution of the lunar orbit.

Figure 5 shows the evolution of the lunar orbit according to Gerstenkorn's first paper as well as possible modifications by resonance effects. In the figure the moon reaches the seventh resonance with the earth's spin at $R/R_{\oplus} = 7.5$ ($T = 27.5$ hours) with an orbital inclination $i = 110°$, relative to the earth's equatorial plane. The tidal effect tends to decrease both R and i. The resonance effect counteracts a further decrease in R, but allows a decrease in i. When the inclination decreases, the angular momentum of the earth decreases somewhat, with the result that the earth's spin period lengthens slightly. Hence during the resonance captivity the moon's period and also its distance increases slightly.

When the inclination has decreased to about 40° or 50° the tides tend to increase the moon's distance instead of tending to decrease it as they did earlier. However, the resonance effect still keeps the moon trapped. With further decreasing inclination the resonance locking, however, becomes less efficient, and it can no longer compensate for the tendency of the tides to increase the lunar distance. When the moon finally is set free from the resonance, it follows the interrupted Gerstenkorn development out to the present orbit.

The argument has been raised (*19*) that any capture must be associated with the earliest stage of the history of the earth because the probability that the moon could be stored in another orbit for an extended time would be vanishingly small. This argument is based on the random capture calculations mentioned earlier, and does not consider the effect of resonance phenomena. Since a number of bodies still survive in metastable resonance orbits the probability would not appear negligible that others persisted for a considerable time.

Also it is understandable that those resonances which still survive are interactions with massive planets such as Jupiter and Neptune, while bodies originally in metastable resonance orbits near the earth or Mars would have had considerably smaller but finite lifetime in such orbits.

An independent set of geological observations, indicative of variation in the tidal forces with geologic time, has recently been presented by Cloud (*13*) who uses the elevation of fossil intertidal bioherms (stromatolites) as a measure of the local tidal amplitude. These amplitude data, if arranged in time, suggest a tidal evolution qualitatively similar to that derived from Olson's data: an early capture of the moon (more than 2.3 eons ago) followed by a relatively slow approach toward the earth, culminating in Late Precambrian and followed by decrease of the tidal amplitudes to their present level. The maximum amplitude (6 m) is associated with the South African Otavi series, which has an age estimated between 0.5 and 1.1 eons (*36*). The oldest stromatolite quoted in Cloud's work has an age between 2 and 2.5 eons. Similar structures of considerably greater age have been described (*37*); however, the identification of these as stromatolites does not appear to have been generally accepted in the past. Recent investigations by Engel (*20, 38*) have according to him removed any doubt that the structures in question are algal stromatolites; he considers their age with certainty to be greater than 2.7 eons. It is interesting to note that these oldest observed stromatolites have an elevation of only 3 to 4 cm, suggesting that tidal forces were practically absent at least in this environment during this early period of the earth's history. Because it is clear from the discussion above that an isolated observation of tidal amplitude cannot be generalized on a worldwide basis, a quantitative interpretation of the stromatolite data in terms of lunar orbital evolution must, however, by necessity be tentative.

It has also been pointed out (*14*) that the stromatolites cannot have developed in an environment with tidal waves of the size invoked to explain the widespread continental erosion and conglomerate deposition (*11*); to be compatible these two groups of phenomena must consequently be assumed separate geographically or temporally.

Comparison of the Two Alternatives

As shown above, we cannot exclude the possibility that the moon passed through the Roche limit and that a catastrophe took place with the following results:

1) Tides were very high, but due to the geographical distribution of continents they were confined to limited regions.

2) The moon melted, but possibly only the surface layers.

3) The moon broke up. Fragments from the inner tidal bulge were ejected into orbits inside the lunar orbit. Some of the fragments may have been scattered into collision with the earth but most of them were later intercepted by the moon as a consequence of orbital precession, producing at least some of the lunar craters.

4) Fragments from the outer tidal bulge were ejected into orbits outside the lunar orbit. Some of them were recovered by the moon but many were thrown into interplanetary space. They were stored, at least in part, in resonance orbits near the earth's orbit and were scattered into capture in the course of geological time. At least some types of meteorites could originate by this process.

5) If this conclusion is correct, the meteorite exposure age dates the close lunar approach to Late Precambrian, supporting Olson's (*11*) identification. If on the other hand the meteorite evidence is discarded, the dating of the Gerstenkorn event would rely entirely on evidence from the geological and selenological records.

The noncatastrophic alternative has the following advantages and disadvantages:

1) The tides never need to be very high, and the heating of both the moon and the earth is negligible. The close approach, characterized at least regionally by moderately high tides, would be stretched out over a considerable length of time, perhaps a large fraction of an eon.

2) The structure of the moon has not been extensively altered after its original aggregation as an independent planet. The craters of the moon are produced in the final stage of this process by planetesimal impact in the same way as the craters of Mars.

3) The meteorites do not originate from a lunar break-up.

Decision between the Alternatives

Radiometric dating of igneous lunar rocks will hopefully provide information on the time of their solidification. If the catastrophic alternative is correct, the majority of lunar igneous rocks should date to considerably less than 4.5 eons, the minimum age of the planet moon. In case the proposed geological identification and associated origin of meteorites are correct, the predominant age should be around 0.7 eon. Further, the ages of the major surface and subsurface features of the moon should be less than 0.7 eon.

If on the other hand the noncatastrophic alternative is correct, the predominant age of lunar crustal rocks should exceed 4 eons, perhaps considerably, as it is likely that the moon is older than the earth (*6*). Local melting features with lower age would in this case be associated with meteorite impact events spread over geological time.

References and Notes

1. H. Gerstenkorn, *Z. Astrophys.* **36**, 245 (1955).
2. G. J. F. MacDonald, in *The Earth-Moon System*, B. G. Marsden and A. G. W. Cameron, Eds. (Plenum Press, New York, 1966).
3. P. Goldreich, *Rev. Geophys.* **4**, 411 (1966).
4. S. F. Singer, *Geophys. J. Roy. Astron. Soc.* **15**, 205 (1968).
5. H. Gerstenkorn, in *Mantles of the Earth and Terrestrial Planets*, S. K. Runcorn, Ed. (Interscience, New York, 1967); ——, *Icarus* **9**, 394 (1968); *ibid.* **7**, 160 (1967); ——, *ibid.* **6**, 92 and 292 (1967).
6. H. Alfvén, *On the Origin of the Solar System* (Oxford Univ. Press, Oxford, 1954).
7. ——, *Astrophys. J.* **136**, 1005 (1962); ——, *Science* **148**, 476 (1965).
8. ——, *Icarus* **1**, 357 (1963).
9. P. Goldreich, *ibid.* **9**, 391 (1968).
10. H. von Eckermann, *Geol. Fören. Stockholm Förh.* **59**, 548 (1937); D. L. Lamar, P. M. Merifield, *Bull. Geol. Soc. Amer.* **78**, 1359 (1967).
11. W. S. Olson, *Amer. Sci.* **59**, 458 (1966).
12. ——, *Science* **161**, 1364 (1968).
13. P. E. Cloud, *ibid.* **160**, 729 (1968); see particularly p. 731 and table 1; the age of the Otavi series is not indicated, but is given in (*36*).
14. ——, *ibid.* **161**, 1364 (1968).
15. W. Munk, *Quart. J. Roy. Astron. Soc.* **9**, 352 (1968).
16. See, for example, review by K. M. Creer, in *Mantles of the Earth and Terrestrial Planets*, S. K. Runcorn, Ed. (Interscience, New York, 1967).
17. W. M. Elsasser, in *Advances in Earth Science*, P. M. Hurley, Ed. (M.I.T. Press, Cambridge, 1966).
18. H. Gerstenkorn, *Icarus*, in press.
19. H. C. Urey and G. J. F. MacDonald, in *Physics and Astronomy of the Moon*, Z. Kopal, Ed. (Academic Press, New York, in press).
20. A. E. J. Engel, B. Nagy, L. A. Nagy, C. G. Engel, G. O. W. Kremp, C. M. Drew, *Science* **161**, 1005 (1968).
21. R. B. Baldwin, *The Measure of the Moon* (Univ. of Chicago Press, Chicago, 1963).
22. D. S. Burnett and G. J. Wasserburg, *Earth Planet. Sci. Lett.* **2**, 137 (1967).
23. D. Heymann, *Icarus* **6**, 189 (1967).
24. H. Voshage, *Z. Naturforsch.* **22a**, 477 (1967).
25. R. J. Jaeger and E. Lipschutz, *Geochim. Cosmochim. Acta* **31**, 1811 (1967).
26. P. Eberhardt and D. C. Hess, *Astrophys. J.* **131**, 38 (1960).
27. H. C. Urey, *Naturwissenschaften* **55**, 49 (1968).
28. E. J. Öpik, *Proc. Roy. Irish Acad.* **54A**, 165 (1951).
29. J. R. Arnold, in *Isotopic and Cosmic Chemistry*, H. Craig, S. L. Miller, G. J. Wasserburg, Eds. (North-Holland, Amsterdam, 1964); ——, *Astrophys. J.* **141**, 1536 and 1548 (1965).
30. W. M. Kaula, *An Introduction to Planetary Physics* (Wiley, New York, 1968).
31. J. Schubart, *Astron. J.* **73**, 99 (1968).
32. G. Colombo and I. I. Shapiro, *Astrophys. J.* **145**, 296 (1966); P. Goldreich and S. Peale, *Astron. J.* **71**, 425 (1966); ——, *ibid.* **72**, 662 (1967).
33. R. R. Allan, *Planet. Space Sci.* **15**, 53 (1967).
34. G. Pannella, C. MacClintock, M. N. Thompson, *Science* **162**, 792 (1968).
35. T. B. McCord, *Astron. J.* **71**, 585 (1966).
36. H. Martin, *The Precambrian Geology of Southwest Africa and Namaqualand* (The Precambrian Research Unit, University of Cape Town, 1965).
37. A. M. MacGregor, *Trans. Geol. Soc. S. Africa* **43**, 9 (1940).
38. A. E. J. Engel, personal communication (1968).
39. A. Defant, *Physical Oceanography* (Pergamon, New York, 1961), vol. 1.

40. Supported by NASA grant NGL 05-009-002.