The Origin of the Moon

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The origin of the moon is considered within the theory of formation of the terrestrial planets by accumulation of planetesimals. The theory predicts the occurrence of giant impacts, suggesting that the moon formed after a roughly Mars-sized body impacted on the protoearth. The impact blasted portions of the protoearth and the impacting body into geocentric orbit, forming a prelunar disk from which the moon later accreted. Although other mechanisms for formation of the moon appear to be dynamically impossible or implausible, fundamental questions must be answered before a giant impact origin can be considered both possible and probable.

THE SCIENTIFIC JUSTIFICATION FOR THE APOLLO MISSIONS to the moon was largely to determine how the moon originated. Sixteen years after the first Apollo landing, the theory of the formation of the terrestrial planets appears to have advanced sufficiently to provide an answer to the question of lunar formation (*1*). While many important details remain to be investigated, it now appears that the moon was formed after a giant impact of a roughly Mars-sized body on the protoearth (*2*). The impact injected a significant fraction of the mass of the impactor and the protoearth into geocentric orbit, where it later coagulated into the moon. Recent work has considerably strengthened the view that the older hypotheses of lunar origin (fission, capture, and binary accretion) are either physically impossible or extremely improbable.

The general theory of terrestrial planet formation provides the framework in which to consider lunar formation. This theory could very well change in the future; if so, the conclusions of this article may require revision. Given our present understanding, however, a consistent picture of lunar formation may be drawn.

A key element in the giant impact hypothesis of lunar origin is the mass distribution of the smaller bodies, termed planetesimals, from which the terrestrial planets formed. While it has been thought that the terrestrial planets accumulated primarily from very small planetesimals, giant impacts are likely to have occurred only if most of the planetesimal mass was in bodies not much smaller than the largest protoplanet. A distribution of planetesimal mass that favors giant impacts now appears to have been the case (*3*). Much of the detailed physics and chemistry associated with the giant impact hypothesis is yet to be studied, but the exploratory work completed so far has not revealed any fatal flaws in the hypothesis. It is quite possible that the next decade of work on this problem will yield a generally acceptable model of the formation of the moon.

Early Phases of Formation

The formation of the Earth-moon system is considered a natural part of the overall process that formed the sun and the rest of the solar system. Because the formation of the Earth-moon system should not be considered a "special case," independent of the processes that formed the rest of the terrestrial bodies, we begin with a description of the early phases of evolution of the material that eventually formed the moon and the terrestrial planets.

About 4.6 × 10^9 years ago, a slowly rotating, cold, dense portion of an interstellar cloud of gas and dust began to contract and collapse to higher densities as a result of internal gravitation. Matter with low angular momentum collected at the center of the protostellar cloud and eventually formed the sun. The protosun was surrounded by a rotationally flattened disk of gas and dust, termed the solar nebula, from which the moon and planets formed. The protosun is usually thought to have had little direct effect on the formation of the planets, save for the possibility of its experiencing a T Tauri wind phase, where a greatly enhanced solar wind could have blown away any gaseous portion of the solar nebula. The estimated ages of T Tauri stars imply that, if the sun experienced a T Tauri wind phase, it must have occurred during the first 10^6 years or so of protostellar evolution. Otherwise, the role of the sun was to provide a point source of gravity that dominated the orbital dynamics of the solar nebula.

Because of their physical and orbital similarities, Mercury, Venus, Earth-moon, and Mars each must have been formed by the same basic processes. Most of the research on terrestrial planet formation has assumed that formation proceeded by accumulation of dust grains (*4, 5*) rather than by gravitational collapse of gas in the solar nebula and subsequent removal of a gaseous envelope (*6*). One problem with the theory of gravitational collapse is that it seems to require that the solar nebula have a mass approximately equal to 0.1 solar mass, which after collapse must somehow be dispersed. Accumulation of the terrestrial planets by dust grains requires that much less postplanetary debris be removed from the inner portion of the solar nebula.

After the solar nebula forms and after any turbulent motions cease, the gas and dust grains separate because the gas is thermally supported and forms a relatively thick disk, while the dust grains are unsupported and sediment down to form a much thinner disk in the midplane of the nebula. Concurrent with the sedimentation process, dust grains initiate the actual process of planetary accumulation by coagulating after collisions, with intermolecular (van der Waals) forces being responsible for holding the grains together in this phase. The process of sedimentation and initial growth to diameters of about 1 cm is thought to require about 10^3 years (*4, 7*).

As more grains sediment down to the midplane, the dust layer eventually becomes dense enough to be gravitationally unstable, meaning that areas of small density enhancements will be drawn together into clumps. This instability is thought to occur in two stages (*4, 8*). The first stage produces clumps up to about 0.1 km in diameter that are largely supported by their rotation. These clumps are also gravitationally unstable and, providing that gas drag and mutual collisions can redistribute their angular momentum, within a few thousand years should form dense (about 3 g cm^{-3}) planetesi-

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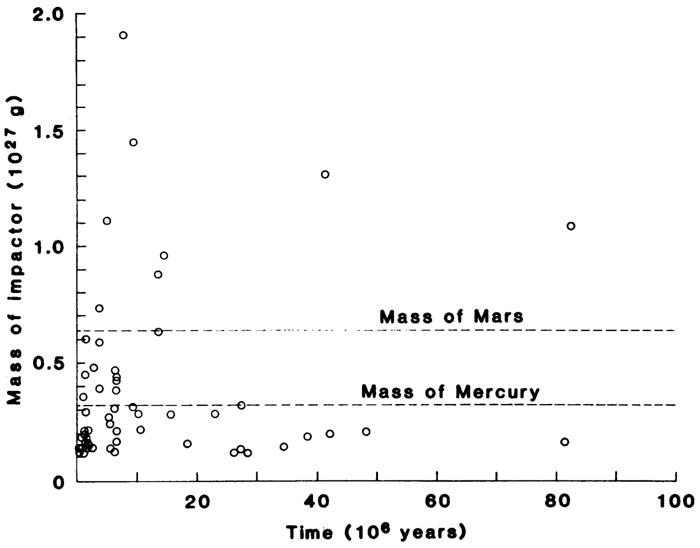

Fig. 1. Giant impacts on Earth after accumulation from a swarm of planetesimals ranging in mass and heliocentric distance from 10^{26} g (0.70 to 0.75 AU) to 10^{25} g (1.15 to 1.20 AU). Similar distributions of giant impacts were found for other initial mass distributions (*3*). Results are from five accumulation calculations.

mals on the order of 5 km in size with very nearly circular orbits.

These first planetesimals are relatively closely packed in the midplane of the solar nebula, and interactions between them resemble those in a very cold, ideal gas. Because of the small eccentricity of the planetesimals' heliocentric orbits, this phase of the accumulation process can be accurately modeled by a statistical theory based on the interactions of particles in a box (*4*), where the box includes all the planetesimals within a very narrow [perhaps $\sim 10^{-4}$ to 10^{-3} astronomical units (AU); 1 AU is the distance between Earth and the sun] ring around the sun. Because of the small masses of the planetesimals in this phase, gravitational perturbations are small and the orbits remain nearly circular; accumulation in each ring proceeds independently of other rings. Collisions between these planetesimals generally lead to accumulation, because kilometer-sized bodies are massive enough that their self-gravity can hold the planetesimals together after collisions at the low relative velocities expected in this phase.

Several studies of the accumulation process in the closely packed phase have resulted in a mass distribution with most of the mass concentrated in the largest bodies, whether or not a dynamically significant gaseous component of the solar nebula remains (*4, 9*). The distribution includes a sharp drop off at the maximum mass, implying that the mass of the second largest body is not much smaller than that of the largest body in each box. Numerical simulations (*10*) have shown that a swarm of bodies 10^{16} g in mass (1 km radius) can accumulate within about 2×10^4 years into bodies up to 10^{24} g in mass (500 km radius). This phase must terminate when all the particles in the ring are accumulated into a single planetesimal, which also leads to a maximum planetesimal mass close to 10^{24} g. About 10^4 planetesimals of this size would be sufficient to form the terrestrial planets.

Safronov (*4*) has suggested that the late stages of the accumulation process would eventually be characterized by runaway accretion, where the largest planetesimal becomes progressively larger than the next largest planetesimal. Runaway growth can occur because, as a planetesimal becomes more massive, its cross section for sweeping up smaller bodies is enhanced above the geometrical cross section by the effects of gravitational focusing. In the two-body approximation, the gravitational cross section can become proportional to r^4 (r, planetesimal radius) compared to r^2 for the geometrical cross section. An early phase of runaway accretion was indeed found in numerical simulations of accumulation in the closely packed phase (*10*). In the Safronov theory (particles in a box), runaway accretion is subdued, with the second largest body being from 0.01 to 0.1 times as massive as Earth (*11*). However, in the more accurate three-body problem (that is, including the sun and orbital motions of the planetesimals), the gravitational cross section may be even larger than that assumed in the two-body approximation (*12*).

If runaway accretion dominated the later phases of accumulation, the terrestrial planets would have formed primarily by the impacts of planetesimals of much smaller mass. While a phase of runaway accretion cannot be definitively ruled out at present, on the basis of the previously cited work we will assume that the late phase of accumulation proceeds from a swarm of planetesimals of nearly equal mass. We will see that this assumption is consistent with the results of several recent studies.

Late Phase of Formation

Although the previous phases of growth required no more than perhaps 10^6 years, subsequent growth proceeded much more slowly. Hence, if the sun experienced a T Tauri phase similar to that of other stars with the same mass, the enhanced solar wind is likely to have started during the previous loosely packed phase, removing any residual nebular gas.

In the final phase of accumulation, the orbital motion of the planetesimals must be included, because the planetesimals have already swept up all the matter within their rings (*5, 13*). Further accumulation requires gravitational perturbations between the planetesimals to raise the eccentricites of their orbits (and hence the relative velocities) enough to permit collisions. If the relative velocities become too large, however, fragmentation after high velocity collisions could stall the accumulation process. It has been shown both analytically and numerically that the dynamics of the accumulation process regulates the relative velocities to intermediate values that allow growth (*4, 5*).

Wetherill (*3*) has numerically studied the evolution in this phase

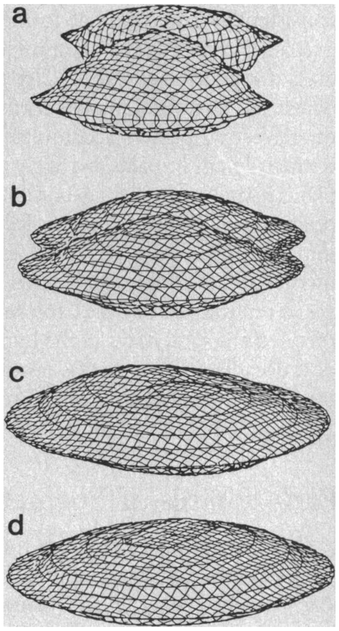

Fig. 2. Time evolution of a rapidly rotating model of the protoearth, equally spaced in time between the initially distorted protoearth (a) and the configuration one rotation period later (d). Because of the presence of dissipation, no dynamical fission instability occurs (*22*).

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(Fig. 1). Starting with a swarm of 500 bodies of mass 2.5×10^{25} g, or a range between 5.7×10^{24} to 1.1×10^{26} g on the basis of the mass distribution in the closely packed phase (*4, 9*), with orbital angular momentum equal to that of the terrestrial planets, the planetesimal swarm stochastically evolves to produce a small number of final planets, often with a strong resemblence to our solar system. No preference for runaway accretion was found; the last phases of accumulation involve impacts of relatively massive planetesimals. This final phase requires on the order of 10^7 to 10^8 years.

The periods of rotation of the newly formed terrestrial planets depend on the distribution of impacts of the planetesimals that formed them. Depending on the details of the impact, planetesimals may contribute either prograde or retrograde angular momentum. The spin angular momentum of a planet formed from a large number of planetesimals will thus undergo a random walk, tending toward prograde spin because of the eccentric heliocentric orbits of the impactors. It is improbable that such a random walk could result in as much angular momentum as exists in the Earth-moon system (*4, 14, 15*). The last phase of accumulation is now thought to involve impacts of planetesimals with masses comparable to or greater than that of Mars (~0.1 Earth mass). The nearly tangential impact of such large bodies leads naturally to the large amount of angular momentum necessary to explain the primordial Earth-moon system.

Rotational Fission

Darwin hypothesized in 1880 (*16*) that the moon formed from the outer layers of a protoearth that was spinning too rapidly to be dynamically stable. This fission hypothesis was based on the classically known dynamical instability of incompressible, inviscid bodies in uniform rotation.

Objections to the fission hypothesis have centered on two concerns. The first is the difficulty in spinning the protoearth rapidly enough to exceed the classical limit for dynamic stability; accumulation from many small planetesimals makes a 2-hour spin period for the protoearth highly improbable. However, because the accumulation process is now thought to involve impacts of relatively large planetesimals, a rapidly spinning protoearth cannot be so easily dismissed, although the fission hypothesis may then be obviated by the giant impact hypothesis.

The second concern is that the amount of angular momentum required for the fission instability is roughly four times that of the present Earth-moon system (*17*), requiring that most of the angular momentum be removed afterward (*18*). Numerical calculations of the dynamic fission instability in inviscid, compressible bodies have shown that the instability results in the ejection of spiral arms containing perhaps 10 percent of the total mass but considerably more angular momentum. Gravitational torques between the spiral arms and a still rapidly rotating, nonaxisymmetric protoearth could transfer further angular momentum outward. Inefficient formation of the moon from the resulting disk could conceivably solve the excess angular momentum problem (*19*).

A third concern, the neglect of viscosity, has been raised recently. If the protoearth was nearly totally molten, its viscosity would have been negligible, as previously assumed. While the impact of a Mars-sized body involved sufficient kinetic energy to melt the entire Earth, the impact process is thought to be inefficient at melting the entire Earth because of losses by radiation and ejecta during the impact (*20*). Furthermore, hot planetary surfaces cool rapidly unless covered by a thick lithosphere, and convection in even partially molten bodies is efficient at removing heat from the interior. Estimates of the minimum viscosity of the early Earth's mantle begin at about 10^{15} poise (*21*); a similar viscosity results for Maxwell and Kelvin-Voigt viscoelastic models when the specific dissipation factor Q is 1 and the dynamic time scale is a few hours.

The dissipative effects of a viscosity of about 10^{15} poise or larger have been simulated (*22*) in rapidly rotating protoearth models (Fig. 2). Both numerical models and analytical models similar to the classical analyses show that, in the presence of substantial dissipation, the dynamic fission instability vanishes. Because fission must occur through a dynamic instability, a fission origin for the moon is apparently impossible unless the protoearth was nearly inviscid. Because bodies much smaller than Earth are even less likely to have been (or remained) molten, this result also removes one mechanism for lowering planetesimal masses during the accumulation process, thereby lending support for planetary accumulation having proceeded as previously outlined.

Capture

Capture into Earth orbit of a moon formed elsewhere in the solar nebula requires dissipation of kinetic energy. The relatively feeble dissipation produced by tidal deformation in a close encounter means that the moon must start from a circular orbit very close to Earth (low relative velocity) if it is to be captured. In that case, it is very improbable that the moon did not previously either collide with Earth or become perturbed to an orbit with high relative velocity, from which capture is impossible.

Tidal disruption after a close encounter with Earth was advanced as a more likely means to inject matter into Earth orbit (*23, 24*). Because of tidal forces, no stable equilibrium exists for a fluid satellite within a critical distance from the primary, termed the Roche limit. For the Earth-moon system, the Roche limit is about 3 Earth radii. It was thus hypothesized that any planetesimal that passed within the Roche limit would be tidally disrupted into a shower of debris, some of which might remain in Earth orbit to form the moon later.

The Roche limit applies to inviscid bodies on circular orbits, however. Studies of the tidal disruption of dissipative planetesimals (*25, 26*) with a simulated viscosity of 10^{14} poise or more (*25*) have

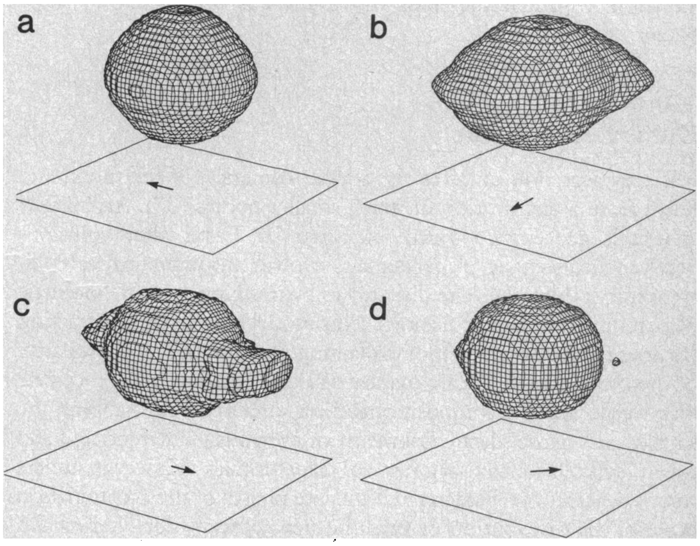

Fig. 3. Time evolution of a dissipative planetesimal passing Earth at grazing incidence (*25*). Arrows point toward Earth. In (b), the planetesimal is closest to Earth and is nearly touching its surface; in (a) and (c) the planetesimal is twice as distant; in (d) it is four times as distant.

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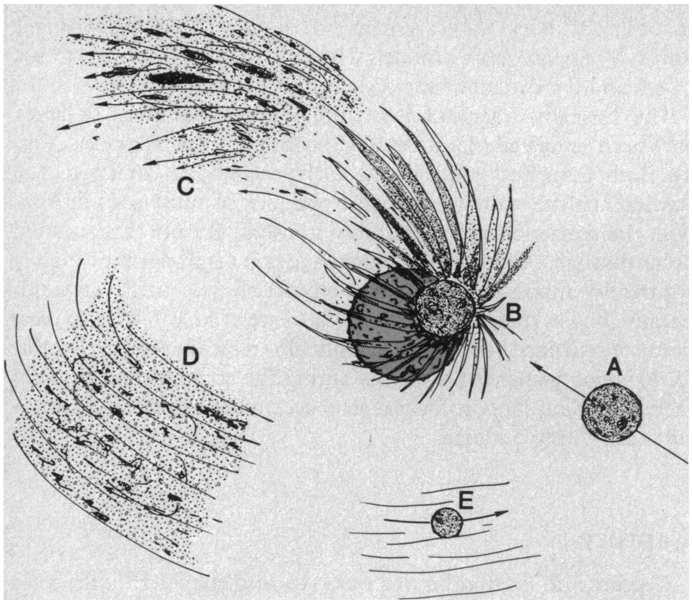

Fig. 4. The giant impact hypothesis of lunar formation. A Mars-sized planetesimal (A) impacts on the protoearth (B) tangentially, resulting in a gigantic explosion and the jetting outward of both planetesimal and protoearth mass. Some fraction of this mass remains in Earth orbit, while the rest escapes Earth or impacts again on Earth's surface (C). A protomoon begins to form from the prelunar disk (D), accretes matter from the prelunar disk, and finally becomes the moon (E).

shown that complete tidal disruption does not occur, even in the extreme case of grazing incidence (Fig. 3). A planetesimal cannot be disrupted in the short period of time involved in a close encounter unless it is molten and hence inviscid, which is unlikely for small bodies.

Because the cross-sectional area of the Roche limit is larger than the geometrical cross section of a protoplanet, several encounters within the Roche limit must occur for every encounter that results in a collision and accumulation. If tidal disruption were efficient, the accumulation process for all the terrestrial planets would presumably be altered. The elimination of tidal disruption for dissipative planetesimals lends further support to the general picture of accumulation in which the mass distribution is dominated by large bodies.

Binary Accretion

Binary accretion involves the coeval formation of the moon and Earth from a distribution of much smaller bodies (*27*). An initially spherical, geocentric swarm, captured by Earth after collisions between heliocentric planetesimals, evolves through further collisions into a thin disk. The disk grows by trapping more heliocentric planetesimals through collisions. This model has the great attraction (as does the fission model) of explaining the bulk chemical similarity of the moon to the silicate mantle of Earth, because the geocentric disk would act as a compositional filter, preferentially trapping the smaller, less dense silicate fragments of previously differentiated and tidally or collisionally fragmented planetesimals. However, unless runaway accretion characterized the late phases of the accumulation process, the distribution of small bodies necessary for filtering did not occur. Other serious objections may be raised as well.

The geocentric disk must not prematurely accumulate into a few large bodies, because then the disk loses its ability to act as a compositional filter. Because the orbital period of planetesimals in geocentric orbit is much shorter than for those in heliocentric orbit, accumulation in Earth orbit occurs on a much shorter time scale than the time scale for which new matter is added to the disk. It has been proposed that accumulation could have been forestalled by repeated high velocity impacts of incoming planetesimals with the protomoon, but roughly 10^6 successive exceptionally energetic impacts appear to be needed (*28*).

Acquiring the angular momentum of the Earth-moon system from impacts of a large number of planetesimals in a geocentric swarm is highly improbable because, as noted before, the net angular momentum conferred by many bodies is likely to be small. If special orbital characteristics for the impactors are specified, such as very low eccentricity or a population depleted in Earth-crossing orbits, sufficient angular momentum might be obtained (*15, 29*). However, low-eccentricity orbits would be quite rare in the late phases of accumulation, and the time scale for repopulating any Earth-crossing orbits that have been depleted by previous impacts with the Earth-swarm system is undoubtedly shorter than the time scale for further impacts because of the greater cross section for close encounters (resulting in orbital perturbations) compared to that for impacts.

Giant Impact

Forming the terrestrial planets through the accumulation of large planetesimals leads naturally to the idea that a giant impact (*2*) could account for lunar formation (Fig. 4). While the giant impact hypothesis includes some features common to some of the older hypotheses, its particular aspects overcome the previous objections. For example, the hypothesis certainly involves capture of matter accumulated elsewhere, but the impact aspect ensures that some matter will enter geocentric orbit. The hypothesis also involves forming the moon from a geocentric disk, as in binary accretion, but the single giant impact accounts at once for all the necessary angular momentum and mass, with the latter possibly being compositionally filtered by prior protoplanetary differentiation.

In order to deposit the angular momentum of the Earth-moon system, a Mars-sized body would have had to strike Earth nearly tangentially with a relative velocity of about 10 km sec^{-1}; this is

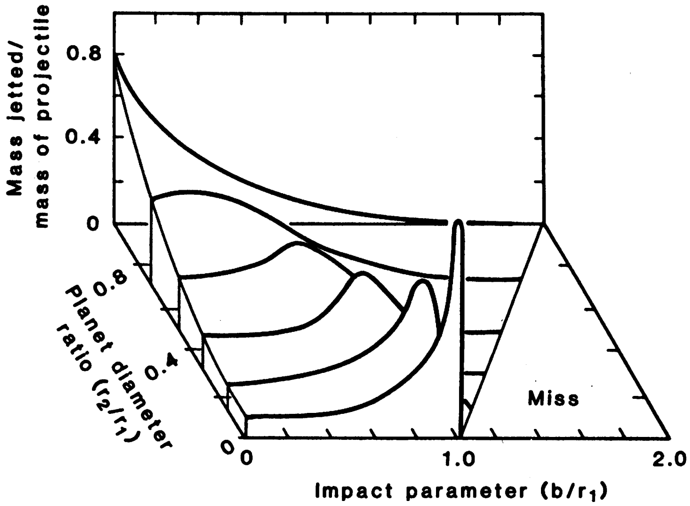

Fig. 5. Total jetted mass for impact of a projectile of radius r_2 on a body of radius r_1 (*31*). For tangential impacts ($b/r_1 \sim 0.8$) of Mars-sized bodies on the protoearth ($r_2/r_1 \sim 0.5$), the amount of jetted mass is close to half the mass of the projectile. [Courtesy of the Lunar and Planetary Institute]

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consistent with the relative velocities of giant impacts in the late phases of accumulation (*3*). Because the mass of Mars is roughly eight times that of the moon, the formation process need not have been very efficient, especially since a body up to three times larger than Mars may have been involved. The giant impact would eject matter from Earth's mantle and from the impactor. Estimates of the amount of a silicate mantle that would be vaporized by an impact at 10 km sec^{-1} imply that several times the mass of the moon could be vaporized by a Mars-sized body (*30*). Models of the matter ejected by jetting during the explosive impact (Fig. 5) predict that, for impact parameters close to tangential, a Mars-sized impactor results in the ejection of mass up to one-half the impactor mass, evenly contributed by Earth and the impactor (*31*).

The debris from a giant impact is at least partially vaporized, which is important because the accelerations associated with pressure gradients in the ejecta appear to be critical for injection into geocentric orbit (debris that is ballistically ejected must either escape Earth or reimpact Earth's surface). Initial stimulations (*32*) of the flow of the ejecta after the explosion have determined that, if the vapor is cool and quickly condenses into particles, thermal pressure does not place sufficient matter in Earth orbit, whereas if the vapor is too hot, the ejecta is blown away from Earth altogether. An intermediate thermodynamic behavior can result in the formation of a prelunar disk of several lunar masses (*32*). If the ejected flows are turbulent, turbulent viscosity in the jets might also aid emplacement in Earth orbit (*33*).

Once a prelunar disk is formed, the portion exterior to the Roche limit is expected to accumulate easily into a protomoon. Matter inside the Roche limit will be tidally prevented from accumulating, and, combined with the dissipation associated with collisions, this might result in an effective viscosity capable of moving matter outward (*34*). The dissipation is likely to be large enough to maintain a mixture of vapor, liquid, and particles in the prelunar disk (*35, 36*). A molten state may result in the devolatilization necessary to account for differences with Earth's mantle (*37*).

The evolution of such a multiphase disk is uncertain. If the disk consists of liquid silicates and bubbles of vaporized silicates, the sound speed of the mixture can be considerably lower than in either phase (*35*). A small sound speed implies low thermal pressure and gravitational instability even for a hot disk. Whether the moon accumulated from liquid or solid matter may then depend on the time scale for moving matter beyond the Roche limit and the cooling time; both times have been estimated to be on the order of 100 years (*35*). Formation of an initially molten moon may be inconsistent with the apparent absence of major thrust faults that would have formed on the lunar surface as the moon cooled and contracted (*38*).

Research on the giant impact hypothesis has yet to encounter any serious obstacles. A great deal of work must be done, however, before the hypothesis can be considered confirmed. Each phase of the hypothetical process must be rigorously studied: the impact and gigantic explosion, the amount and state of the matter ejected thereby, the fraction trapped in geocentric orbit, the dynamical and thermal evolution of the prelunar disk, the final accumulation of the moon, and the chemical and geological implications of forming the moon in this manner. Although we will never be able to state with absolute certainty that we know the origin of the moon, the giant impact hypothesis may well be the most probable one.

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