Mechanical Processes Affecting Differentiation of Protolunar Material [1]

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Mechanisms prior to lunar formation are sought to account for the loss of volatiles, the depletion of iron, and the enrichment of plagioclase. Some of the same mechanisms are necessary to account for achondritic, stony-iron, and iron meteorites. Collisions seem marginally capable of providing the heat to accomplish the differentiation into iron, magnesian silicates, and plagioclase. Once this differentiation is accomplished, the subsequent mechanical history should have been sufficient to sort material according to composition in the protolunar circumterrestrial cloud. Effects operating include the correlation of body size with mechanical strength; the lesser ability of the cloud to trap the larger, denser infalling bodies; the more rapid drawing into the Earth of the larger moonlets; and the higher energy orbits for dominantly plagioclase smaller pieces broken off by collision.

Lunar Structure

An adequate theory of lunar origin must account for three major chemical differences from cosmic or chondritic abundances: (1) the loss of volatiles, (2) the loss of iron, and (3) the gain of plagioclase. As shown by all analyses of lunar samples, the Moon is a very dry place. The oxygen fugacity is extremely low, the only carbon is solar wind implanted, only traces of primordial lead have been found, etc. The mean density of 3.34 g cm^{-3} does not allow more than 14-percent iron, considerably less than the 30 to 35 percent characteristic of the Earth and meteorites. The global lunar magnetic permeability of 1.012 (ref. 1), coupled with seismic velocities indicative of an olivine composition (ref. 2), indicate an iron content as low as 6 percent. The thick crust indicated by gravimetry and altimetry (ref. 3) plus the need for mare basalt source regions to be enriched in lithophiles (refs. 4 and 5) require that at least the outer half of the Moon be enriched about threefold in plagioclase relative to chondrites. Assuming that the 30 ergs/cm^2/s heat flow measured at the Apollo 15 and 17 sites (ref. 6) is representative of the entire globe and thence of the uranium content, and assuming refractory silicate abundance to be proportionate to uranium abundance (ref. 7), the plagioclase enrichment is more than fourfold.

Constraints on origin also come from the present temperature and density structure of the Moon. The crust of 50 or 60 km of anorthositic gabbro (ref. 3) requires that the outer parts be heated enough early in lunar history to accomplish the necessary differentiation. The lithosphere 1000 km thick (ref. 8) requires that this zone have less than a chondritic abundance of radioactive heat sources and, hence, that it be at least partly cleared out of large ion lithophiles. The central asthenosphere of 700 km suggests that this innermost 10 percent of the Moon's bulk formed too cold to participate in the early differentiation and, hence, retained its heat sources, enabling it to warm up to its present state.

[1] Publication No. 1342 of the Institute of Geophysics and Planetary Physics.

Before constructing an hypothesis of lunar origin to account for these data, it is appropriate to review some dynamical considerations and differentiation processes.

Dynamical Considerations

If we accept the uniformitarian principle that the Sun and planets formed from a gas and dust cloud similar to those observed to be assoicated with new stars now, then the planets formed from a nebula of some sort (refs. 9 and 10). In such a context, a dynamically plausible origin of the Moon is one which is a by-product of the Earth's formation (refs. 11 through 14), i.e., the Moon forms from a cloud of matter around the Earth. The process is initiated by collisions between planetesimals close enough to the Earth for energy loss sufficient for capture, but at the same time retaining momentum sufficient to go into geocentric orbit rather than infall. The resulting moonlets then act as an efficient trap for further protolunar material.

If the assumption is made that with mass incrementation to the cloud the angular momentum incrementation is random, then a major portion of the cloud was drawn into the Earth. For a cloud of bodies each with mass m_i, semimajor axis a_i, and angular momentum H_i, of total mass small compared to the planet embryo, where M is the planet

$$\frac{1}{2a_i}\frac{da_i}{dt} \approx -\frac{1}{m_i}\frac{dm_i}{dt} - \frac{1}{2M}\frac{dM}{dt} + \frac{1}{H_i}\frac{dH_i}{dt} \quad (1)$$

embryo mass (ref. 15). Another process which would have drawn satellites toward the Earth if planetesimal velocities were isotropic with respect to the Earth was "drag" on the satellites by the planetesimals. A satellite's orbiting about a planet gives it a systematic motion with respect to the planetesimals, resulting in (ref. 16) where δ is

$$\frac{da_i}{dt} = -\frac{88}{15}\pi\delta[GMR\theta]^{1/2}[r_i^2/m_i] \quad (2)$$

the space density of planetesimals in the nebula beyond the influence of the planet embryo; G is the gravitational constant; R is the radius of the planet embryo; r_i is the satellite radius; and θ is the factor for relative velocities v_{rel} in the planet's zone:

$$v_{rel}^2 = GM/R\theta \quad (3)$$

The factor θ varies from 3 to 10, depending on the amount of gas present (ref. 10). More detailed calculations show that the protolunar swarm must get started when the Earth itself is a rather minor fraction of its final mass—less than 10 percent—if a final Moon as large as the actual is to be attained at the end of the process (refs. 14, 15, and 16). Furthermore, a consequence of equations (1) and (2) was that the Moon formed largely of material that fell into the Earth-Moon system later than the bulk of the Earth's material.

It seems dubious that planetesimal velocities were purely isotropic or that angular momentum incrementation was entirely random, however. The latter is hard to reconcile with the progradeness of nearly all satellite orbits and planetary rotations. Whether small biases affect satellite orbit evolutions needs to be solved in conjunction with the planetary rotation problem, perhaps following the path suggested by Giuli (ref. 17).

A process which moved satellites outward was tidal friction:

$$\frac{da_i}{dt} = 3km_i\left[\frac{G}{M}\right]^{1/2}\frac{R^5}{a_i^{11/2}} \cdot \frac{1}{Q} \quad (4)$$

where k is the planet's Love number and $1/Q$ is the dissipation factor (ref. 18). The sign of equation (4) depends on the body's being outside the geosynchronous distance; the magnitude of $1/Q$ depends on the difference between rotational and orbital rates, ω-n, as well as the thermal state of the Earth.

The final important effect on the growth of moonlets about the Earth and their orbital evolution was collision, with the resulting accretion and fragmentation. Through collisions, a system isolated from outside influence evolves toward the minimum energy state conserving angular momentum—a set of coplanar circular orbits. But if the surface density of matter is sufficient, moonlets and, thence, the Moon form by gravitational instability; i.e., relative velocities become gentle enough by collision that any density perturbation grows by gravitational attraction. The time scale for formation of 10-km-sized moonlets is a few years; for the entire Moon, less than 1000 yr (ref. 19). However, the Earth-Moon system was not isolated, but was continually disturbed by infalls from the heliocentric system. Hence, the formation of the Moon was delayed considerably by continual infalls causing breakup of moonlets and repetition of the settling down process until the infall was too small to inhibit the final formation of the Moon, which then occurred rather rapidly. This rapid formation led to significant heating of the outer parts of the Moon, resulting in differentiation of the crust. The heating was of a magnitude suggested by the accretion formula (ref. 20):

$$\rho\frac{Gu(r)}{r}\cdot\frac{dr}{dt}=\delta\,(T^4-T^4_{\text{equil}}) \qquad (5)$$

However, the actual accretion was not the neat accumulation of small bodies suggested by this formula, but more a rather irregular process entailing a wide mass range of infalling bodies, the largest a significant fraction of the Moon's mass. These infalls supplied energy for the convection associated with the asymmetric crustal differentiation.

Collisions also acted to fragment bodies, of course. The typical planetesimal was rather porous, since its component parts could have come together only by bumping at rather low velocities. Subsequent collisions at higher velocities normally involved bodies differing considerably in size. Hence, the effect of collisions was mainly to chip off pieces from the outer parts of the larger bodies and to fragment only the smaller bodies.

An effect of the porosity was to convert a higher portion of the kinetic energy into heat through melting induced by collapse of voids in the rocks, similar to what is happening on a smaller scale currently on the lunar surface (ref. 21). The portion of bodies involved in collision that was melted was always quite minor. More material received mild heating, leading to metamorphosis as observed in ordinary chondrites. Much more was not significantly heated at all, but fractured and broken off, the greater part of the energy of impact going into the kinetic energy of pieces flying off.

Most of the foregoing applies to smaller planetesimals of not more than a few tens of kilometers in size. In larger bodies more than 100 km in size and, thus, having some gravitational field, repeated impacts by smaller bodies resulted in some heating and in some compaction of the deeper parts from the recurrent vibrations set up.

The collision regime applying to the protolunar swarm was appreciably more violent than that for the planetesimals in heliocentric orbits, due to the enhancement of infall velocities by the Earth's attraction. For bodies in heliocentric orbit, an important energy input to collisions was the development of Jupiter. When Jupiter became more than about one-tenth its present mass, it threw considerable matter at rather high velocities into the inner solar system, knocking out more matter than it added but, through collisions, producing appreciable energy for heating.

A final dynamical effect that may have been important in sorting protolunar material is tidal disruption of large planetesimals passing the Earth within their Roche limit. As emphasized by Wetherill (ref. 22) and Wood and Mitler (ref. 23), such close approaches are considerably more probable than collisions. However, most planetesimals were too small to be significantly affected by tidal disruption.

Differentiation Processes

Processes leading to compositional differentiation can be classified as condensational, planetary, and mechanical, i.e., condensing from the gas phase, melting within a parent body or colliding and blowing off, respectively.

As emphasized by several authors, e.g., Grossman and Larimer (ref. 24), but particularly Anderson (ref. 25) with reference to the Moon, the first condensates are calcium-, aluminum-, and titanium-rich minerals, followed by iron, magnesian silicates, etc. However, it is difficult to imagine the small portion of Ca-Al-Ti minerals drifting to the central plane of a hot gaseous nebula to form sizable planetesimals undisturbed by convection currents, etc. It is also hard to imagine how ionization could be maintained to allow plasma effects to be significant separation mechanisms (ref. 26) in such circumstances. The evidence from the Pueblo de Allende meteorite is that the condensation sequence led to moderate enrichment of some particle compositions, but not to segregation of sizable bodies.

Most drastic differentiations among irons and silicates—terrestrial and lunar rocks, achondritic, stony-iron, and iron meteorites—apparently happened as the consequence of melting in a parent body. In the case of terrestrial and lunar rocks, the general circumstances are fairly evident. In the case of meteorites, we have some evidence of the size of parent bodies in the nickel-iron concentration gradients of the Widmanstätten patterns (refs. 27 and 28). However, the heat source is still a major problem. Aluminum-26 appears to be ruled out by the absence of Magnesium-26 (ref. 29). Electromagnetic induction by the T-Tauri hurricane (ref. 30) still seems somewhat contrived, dependent on solar spin decay and mass outflow, both extrapolated from observations of larger stars (refs. 31 and 32). A remaining possibility is collision, whose effect was enhanced by porosity. So far as the problem of the Moon is concerned, we can take as given by the nickel/iron gradient observations of Wood (ref. 27) and Goldstein and Short (ref. 28), that differentiation by melting occurs in some planetesimals of not more than a few tens of kilometers radius. In addition, we all find it convenient to take, as given by the spectroscopic observations of T-Tauri stars by Kuhi (ref. 32), that an outstreaming of matter occurs after a new star forms, even though an understanding of *why* it occurs is remote.

Whipple (ref. 33) suggested that the differing mechanical strengths of iron and silicates would lead to larger earlier forming bodies having more iron than smaller late-forming bodies. Orowan (ref. 34) and Ruskol (ref. 35) have further pursued this possibility. Offhand, it seems like a rather long regime of repeated coalescence, collision, fragmentation, and recoalescence would have been necessary to make mechanical strength an effective sorting mechanism. However, this inefficiency applies mainly to getting differentiation started. Once there had been perceptible differentiations due to condensational or planetary processes, these mechanical effects would enhance segregation of iron from silicates, at least (but not magnesian silicates from plagioclase, etc.). In regard to the composition of the protolunar swarm, manifestly small low-density silicate bodies were more easily captured than large high-density iron bodies. Furthermore, mechanical sorting in the circumterrestrial swarm would be a much more rapid and effective process than in the heliocentric nebula and would be enhanced by any dynamical effects dependent on moonlet size.

Lunar Formation

We wish to construct a scenario of lunar formation taking into account the foregoing considerations. This scenario is based mainly on the models of Ruskol (refs. 12, 13, and 14). The principal addition is to explore the planetary differentiation processes and related collision effects resulting in plagioclase enrichment, which may also have effects on the iron and volatile depletions in addition to the factors considered by Ruskol (ref. 35). We also should consider the implications of a much more massive nebula, such as hypothesized by Cameron (ref. 9) and Levin (ref. 36).

Condensation of solids in a nebula led fairly rapidly to the formation of planetesimals by gravitational instability. Applying the formulae of Goldreich and Ward (ref. 37) to the vicinity of the Earth's orbit leads to 5-km radii for the initial bodies in a sparse nebula of 10 g/cm² solids (ref. 10) and to 500-km radii for the initial bodies in a massive nebula of 1000 g/cm² solids (ref. 9). Mutual perturbations between planetesimals led to the development of relative velocities on the order of $[Gm/r\theta]^{1/2}$, in accord with equation (3). Assuming the higher values of θ dependent on the presence of gas, the initial relative velocities were on the order of 100 cm/s in the sparse nebula and 2×10^4 cm/s in the massive nebula. Using Safronov's (ref. 10) formulae, the resulting formation times for the Earth are 10^8 yr in the sparse nebula and 2×10^4 yr in the massive nebula. (Cameron's figure of 10^3 yr depends on the suppression of all planetesimals but one by an unexplained mechanism.) These growth times are not directly comparable; growth in the sparse nebula terminates because of exhaustion of the solid matter in the zone, while growth in the massive nebula terminates because the remaining material is removed by external causes, presumably a super solar wind.

Our concern is means for heating of planetesimals which are protolunar material in the nebula. The lifetime formulae assume that the terrestrial zone is isolated. In the massive nebula case, there is ample matter for collisions to cause considerable heating: indeed, it is a necessary part of that hypothesis that material be sufficiently pulverized by collision to be blown away. In the sparse nebula case, relative velocities sufficient for collisional heating, say, 1 km/s, occurred when the Earth was only about 2 percent its final mass, if we assume a θ of 4 (appropriate for no gas) in equation (3). The amount of mass per unit time collided with by a larger planetesimal of radius s at this stage is $v_{\mathrm{rel}}\pi s^2 \delta$. The space density δ itself is inversely proportionate to the height of the nebula, $R\ v_{\mathrm{rel}}/v_{\mathrm{orb}} \sim R/30$, where R is the radius of the Earth's orbit, whence

$$\dot{m} = \pi s^2 \varsigma v_{\mathrm{ORB}}/R \qquad (6)$$

Using 10 g/cm² for ς and 720 km for s (i.e., a body with 1 km/s escape velocity), we get 3.3×10^{10} g/s for $\dot{m}$. If this mass influx rate were distributed in small bodies, the heating would be negligible. The heating must be in impacts by bodies of comparable size or not much smaller, and the amount of heat retained is on the order of the change in potential energies upon combination (ref. 19):

$$E = \frac{3}{5} G \left[\frac{(\mu_1 + \mu_2)^2}{s} - \frac{\mu_1^2}{s_1} - \frac{\mu_2^2}{s_2} \right] \qquad (7)$$

For a combination of $s_1 = 720$ km and $s_2 = 360$ km, the energy thus gained is 1.8×10^{33} ergs, or only 3.3×10^8 ergs/g. However, the energy dissipation is highly concentrated near the interface of the collision, most of it in less than 10 percent of the mass. In addition, some of the kinetic energy of approach is trapped if the bodies are porous. If repeated impacts occurred, it is plausible that the outer 100 km or so of planetesimals were heated sufficiently to differentiate plagioclase and iron and to outgas volatiles.

An additional source of energy was bodies thrown into the inner solar system by Jupiter. Such bodies had relative velocities of approach of about 10 km/s; hence, their effect on mass growth was disrupting rather than contributing. However, they would have contributed significantly to heating. They also would have been important in breaking off compositionally different parts of planetesimals from one another and in sorting them by size: the irons tending to be larger because of mechanical strength and the silicates smaller. Due to the longer time scale of Jupiter's formation, these effects probably were not important until the late stages of Earth and Moon formation. A possibility worth exploring is that the protolunar cloud was then enriched by plagioclase-rich material perturbed by Jupiter.

Hence, from dynamical reasoning as well as the evidence of the nonchondritic meteorites, the protolunar material would have arrived in the Earth's vicinity somewhat sorted in composition. Any geocentric belt of matter would have effected further sorting, since it was more capable of catching small silicate chunks than large iron chunks. There would also at this stage have been some discrimination between magnesian silicates and plagioclase; a greater portion of the latter would be in small pieces chipped from the surfaces of planetesimals and, hence, more easily caught.

For the material in orbit about the Earth, the collision regime was qualitatively similar to that of the planetesimals in orbit about the Sun, but two orders-of-magnitude (at least) faster, due to the much shorter cycle time. Higher energy infalls from outside the system had a disrupting and heating effect analogous to the Jupiter intrusions into the inner solar system. Additional effects were the gravitational tightening of the planet-satellite system, planetesimal drag, and tidal friction, expressed by equations (1), (2), and (4). Equation (1) suggests that if dm/dt were proportionate to the cross section area, or $m^{2/3}$, then smaller bodies would be drawn into the Earth more quickly, since da/dt would then be proportionate to $m^{-1/3}$. However, the high velocities of infall make it quite unlikely that the growth rate would be proportionate to $m^{2/3}$. Rather, taking into account the effect on collision of moonlet size relative to infalling body size, the correlation of the stronger material iron with size of body and gravitational binding energy, dm_i/dt, would be likely to have an exponential dependence m_i^n of $n > 1$. In other words, the smaller bodies would have tended more toward elastic collisions and the larger bodies toward inelastic collisions. Hence, equation (1) acted more to remove the larger bodies from the circumterrestrial swarm. However, equation (2) acted more to remove the smaller bodies.

Layered differentiation of moonlets would also have occurred, with the plagioclase rising to the outer parts and the iron sinking to the deeper parts. Upon collision, small pieces would have been chipped off the outer parts of these moonlets. These chipped pieces would have had higher energy per unit mass, relative to the Earth, than the average and, thus, would have taken up orbits on the whole farther out than their parent moonlet. As a result, a larger-than-average portion of them would survive being drawn back into the Earth and therefore would have been finally incorporated in the Moon. These pieces would have had a higher-than-average plagioclase content and lower-than-average iron content.

Additional effects of significance for moonlets coming close to the Earth may be tidal disruption and atmospheric drag. Tidal disruption of a single large planetesimal coming close to the Earth from a low approach velocity has been proposed by Wood and Mitler (ref. 23) as a means of obtaining all the protolunar material. However, the low approach velocity implies that this large planetesimal was formed in the Earth's zone; it is extremely improbable that such a big body, 100 times as massive as allowed by Safronov's $(2\theta)^3$ rule (ref. 10), could have found sufficient low-velocity material to collect itself. So far as our hypothesis goes, the effect merely constrains moonlets to be less than about 200 km in size so long as they are inside the Roche limit. Once they have moved beyond the limit, they can combine into larger bodies, as in Öpik's models (ref. 38).

Atmospheric drag acts, of course, to draw down the smaller silicate bodies preferentially, contrary to the eventuality required by lunar composition. A massive atmosphere, as hypothesized by Ringwood (refs. 39, 40, and 41), might exert such an influence, even if it did not gain enough energy to leave the Earth. Although core formation undoubtedly was of major importance in determining the Earth's convective regime for the first 10^9 yr or more, there is no way any significant fraction of this energy could have been concentrated sufficiently to blast volatiles off the Earth. (Even if it could have been, the maximum mass raised to escape would be only 0.06 Earth mass.) The core formation energy was released throughout the body; it was brought to the surface by convection in an almost liquid mantle where it was exchanged with a vigorously convecting atmosphere that radiated it away. However, although this convection was vigorous by planetary standards, the energy density of the process was small compared to stars, and the rate of mass outflux negligible. The Earth could not have developed an expanding corona.

Hence, the planetesimal collision processes discussed earlier must have also operated to remove volatiles from proto-Earth material. Possibly the Earth's present volatiles were carried by the initial infalling planetesimals, while the later infalling planetesimals were already rather dried out. This raises the problem of why an atmosphere did not form by outgassing of the early infalls and remain while subsequent infalls occurred: why is the Earth so depleted in xenon relative to chondrites, let alone the Sun? Perhaps the devolatilizing of the inner solar system took place when no bodies more than 1000 km or so in radius existed; the initial conglomeration of such planetesimals to make the Earth's center was at too low velocity to cause much outgassing (say about 20 such bodies, constituting 10 percent of the Earth's mass), while the outer bulk of the Earth was made of planetesimals that were all second or later generation, already well outgassed by earlier collisions.

The alternative hypothesis that the Earth and the Moon acquired their volatiles as a veneer from late infalling matter (refs. 7, 42, and 43) requires that the compounds of active volatiles, HCNO, must have been protected from whatever blew away the inert gases. Also, since the Moon has a much higher proportion of late matter than the Earth, the lunar material must have suffered its volatile loss relative to the Earth by processes associated with its geocentric orbit. This loss requires not only heating and breakup, but also sweeping out of the satellite zone so that recondensation onto the protolunar matter does not occur.

To return to the lunar formation problem, any early Earth atmosphere, no matter how hot and seething, would not have had a scale height more than say 100 km, corresponding to silica at 2000 K. Hence, its ability to reach to satellite material at the geosynchronous distance for the 5-hour day, 2.3 R_e, would have been slight.

Conclusions

To summarize, the circumterrestrial ring of matter about the early Earth was already appreciably devolatilized, enriched in silicates relative to iron, and probably enriched in plagioclase relative to magnesian silicates by processes occurring in planetesimals in heliocentric orbit and by some selectivity in capturing such planetesimals and their fragments. While the material was in orbit about the Earth, the outer parts of the cloud which constituted the protolunar material suffered loss of iron due to the more rapidly growing bodies' being drawn into the Earth and experienced gain in plagioclase due to the outermost fragments of moonlets subject to collision being put in higher energy orbits. Also during this time appreciable further loss of volatiles occurred. The material that finally got together to form the Moon during a lull of infalls from outside the Earth-Moon system did so rather rapidly so that the outer parts of the Moon were heated sufficiently to bring much of the excess plagioclase up to form the thick crust.

The hypothesis presented here may seem to depend too much on multistage collision processes difficult to model mathematically. However, given the fundamental hypothesis that the planets and satellites were made from a dust and gas solar nebula, it seems unavoidable that the processes described herein occurred; the problem is the quantitative importance of the processes relative to one another.

Acknowledgment

Discussions with A. W. Harris have been helpful. This research is supported by NASA grant NGL 05–007–002.

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