Riddles About the Origin and Thermal History of the Moon

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Analyses of lunar rocks have confirmed that the interior of the Moon has been subjected to magmatic differentiation, as has been determined by calculation of the thermal history of the Moon. However, it appears that differentiation occurred so early that it could not have been related to heating by long-lived radioactive elements, but rather indicates a high initial temperature of the Moon. The reasons for the high initial temperature remain unknown. The presence of a central, partially melted area revealed by seismic observations forces us to reject convective models of the Moon, while the dimensions of this area, together with the measured heat fluxes from the interior, serve as "boundary conditions" for any new calculations of the thermal history for a two-layered differentiated model of the Moon operative over the past 3.5 billion years. If we start with the early differentiation of the Moon and the high content of long-lived radioactive elements in it, explanation of its current thermal properties represents no difficulty. But these prerequisites themselves remain unexplained.

Due to the continuing controversy concerning the true nature of the process of magmatic differentiation of the Moon, estimation of the composition of the entire Moon on the basis of analyses of surface rock remains unreliable, and use of these estimates to clarify the origin of the Moon is premature. Existing hypotheses concerning the origin of the Moon encounter dynamic difficulties, as well as difficulties with explanation of the high initial temperature, to say nothing of the difficulty involved in explaining the proposed differences in the composition of the Earth and Moon.

New data on the Moon produced by its direct investigation have confirmed some important conclusions drawn earlier on the basis of thermal history (ref. 1) calculations. In particular, they have confirmed that the Moon has undergone magmatic differentiation and that even at present its interior is partially melted.

However, direct investigations have also led to several very important changes in earlier concepts about the evolution of the Moon. Some of these changes have generated new difficulties for hypotheses about the origin of the Moon, whereas the influence of the rest depends on the results of discussions concerning their interpretation. It is not yet possible to propose a new scheme of the origin and evolution of the Moon that considers all the new data and agrees with our concepts of the origin of the other members of the solar system. It is in this much broader area, the overall area of planetary cosmogony, that the current situation is most unclear and contradictory.

New Data About the Moon and Earlier Calculations of its Thermal History

THE HIGH INITIAL TEMPERATURE OF THE MOON

The petrological and chemical composition of the lunar samples returned to Earth has confirmed that the Moon underwent partial melting and magmatic differentiation. However, measurement of the ages of lunar samples has shown that the differentiation did not occur 2 to 3 b.y. ago, as was obtained by calculations of the thermal history of an initially cold Moon with chondritic radioactivity (refs. 2 through 10), but significantly earlier —possibly even during the formation of the Moon. Such early magmatic differentiation requires a high initial temperature of the Moon or very rapid heating immediately after formation. This is a new and very difficult "boundary condition" that must be considered by any hypothesis of the origin of the Moon.

About 3 years ago, when the great thickness of the lunar crust was still unknown, it seemed necessary to assume not only a high initial temperature of the Moon, but also a very surprising radial temperature distribution with a maximum near the surface. This last assumption was related to the fact that the anorthositic lunar crust was formed simultaneously or nearly simultaneously with the formation of the entire Moon, while the maria basalts flowed out about a billion years later. The idea developed that the crust was formed as a result of differentiation of the outer few hundred kilometers, which were initially heated, whereas the basalts were separated from deeper areas, which were initially colder and only later were heated by radiogenic heat. Attempts were made to explain this temperature distribution by the liberation of gravitational energy during accumulation (ref. 11). The released gravitational energy, i.e., the energy per unit of falling mass, does increase as an accumulating body grows. But, in order that the energy released on the surface will not be lost to space but will heat the Moon, unacceptably rapid accretion is required. According to the calculations of Mizutani et al. (ref. 12), Toksöz et al. (refs. 13 and 14), and Toksöz and Solomon (ref. 15), the accumulation could not have lasted more than a few hundred years. Although these calculations were made for highly artificial models of the process of accumulation, they can be considered as satisfactory estimates of the order of magnitude of the duration of accumulation necessary to heat the Moon due to gravitational energy.

When seismic observations showed that the thickness of the lunar crust is about 65 km (refs. 16 and 14), the proponents of the idea of its formation as a result of differentiation of the outer layers of the Moon alone were forced to come up with the additional hypothesis that these layers were from the very beginning rich in calcium and aluminum minerals, i.e., to set forth the hypothesis of heterogeneous accumulation of the Moon. In this case, as noted by Wood (ref. 17), why should the lower temperature condensates accumulate first, followed by material rich in calcium and aluminum which should have condensed earlier?

Many researchers preferred another model. In it, the composition of the Moon is assumed to have been initially homogeneous, and the crust is considered to be a product of primary differentiation of all or almost all of the Moon, whereas the maria basalts are considered a product of later differentiation of the matter that remained deep in the Moon after separation of the crust. In recent years, petrographic and chemical data have accumulated in favor of this second point of view as against the hypotheses of heterogeneous accumulation. They are summarized and literature references given in the article of Brett (ref. 18).

If the lunar crust arose as a result of differentiation of all or almost all of an initially homogeneous Moon, one escapes the requirement of the surprising initial distribution of temperature with its maximum near the surface. Perhaps a high initial temperature for the entire lunar interior would be sufficient. Some calculations of Mayeva for this initial temperature are presented in an article by Levin (ref. 1). However, in any case the explanation of the high initial temperature of the Moon encounters difficulties that are discussed in this same article. Levin has discarded the possibility of heating of the Moon by aluminum 26 or by an intensive solar wind possibly emitted by the young

Sun, as well as the possibility of accumulation of the Moon from hot particles (before the cooling of the protoplanetary cloud). He prefers heating by gravitational energy during accumulation and heating by tidal deformations, although both of these possibilities also encounter significant difficulties.

It should be recalled that the source of energy for early heating is a problem not only for the Moon, but also for the asteroids, which are the parent bodies of the meteorites (ref. 19). Neither heating by the gravitational energy liberated upon accumulation nor heating by tidal deformations can be utilized to explain the heating of the asteroids. We must consider here not only the heating of the interiors of asteriods to approximately 800 to 1000°C as required to explain the thermal metamorphism of the meteorites, but also the melting required to explain the presumed basalt cover of Vesta (ref. 20) and the lava flows on the surface of the parent asteroid of the Ibitira meteorite, which consists of vesicular basalt (ref. 21).

Quite recently, the surface of Mercury was photographed from closeup. These photographs, produced and transmitted to earth by Mariner 10, showed that there are solidified lava flows on the surface of Mercury[1]. It shows that magmatic differentiation occurred on Mercury, which does not agree with the model of the thermal history of this planet calculated a few years ago by Mayeva (ref. 22). Although the Mayeva model assumed a high initial temperature of Mercury, namely 1000 K, it was found that the interior of the planet, according to this model, was never heated to the melting point. Judging from the photographs of Mercury, the lava flows apparently were already occurring during the era of intensive bombardment and cratering. In this case, the initial temperature of Mercury was apparently even higher than was assumed in the model of Mayeva. A high content of radioactive elements (Mayeva assumed chondritic composition for the rocky portion of the matter) would produce melting of the interior of the planet too late, i.e., after the end of intensive cratering. Thus, the question of early heating applies to Mercury as well as to the Moon and the asteroids.

If we seek a single explanation of the early heating of the Moon and the asteroids, we must turn to the same three possibilities that were rejected by Levin (ref. 1) or seek some principally new path, which is presently escaping attention.

Among the possibilities rejected by Levin, the most promising means for heating the Moon and asteroids is heating by short-lived radioactive isotopes. Although the idea that heating by aluminum 26 played an important role during the time of formation of the solar system has now been rejected (refs. 23 and 24), there are continued attempts to confirm the past existence or superheavy radioactive isotopes in the "island of stability" near atomic number $Z = 114$ (refs. 25, 26, and 27). However, in order to heat small bodies, the half life of these isotopes would have to be on the order of 10^6 yr, and, at the same time, their initial abundance would have to be just enough to allow them to exist, in quantities sufficient for heating, for more than 10 half-life periods, i.e., more than 10^7 yr after their nucleosynthesis. (The so-called "formation interval," i.e., the interval of time between the last explosion of a supernova star, which added fresh nucleosynthesis products to the matter of the future solar system, and the beginning of retention of radiogenic isotopes is about 10^8 yr.) Thus, by the time of formation of the Moon and the asteroids, the radioactive isotopes capable of heating them should have almost completely decayed if they were formed during the supernova explosion just mentioned. At the same time, it is difficult to imagine that they could have formed as a result of nuclear reactions in the interstellar nebula.

A similar difficulty arises in attempts to attribute the heating to an intensive solar wind because the characteristic time of attenuation of the latter is on the order of 10^7 yr. Furthermore, induction of sufficiently strong electric currents in the Moon and the asteroids would require that their substance

[1] See the report of B. Murray et al., at this conference.

be initially heated to approximately 500°C in order to provide sufficient conductivity. Thus, yet another source of energy is needed. Doubling of this unknown "initial" heating is sufficient to entirely eliminate heating by the solar wind.

THE PRESENT PARTIALLY MELTED STATE OF THE CENTRAL PART OF THE MOON

Seismic studies of the Moon have shown that at the present time it has a partially molten central area, as was indicated earlier by most calculations of the thermal history for conductive models (ref. 2 through 10 and 28). These calculations give widely varying thicknesses of the outer solid layer for different models: from 120 km to a completely solid Moon. In the models that seemed most probable 10 to 15 years ago, the thickness of the solid layer was 500 to 700 km (refs. 2, 3, 6, 7, and 28), but later, after the presumed thermal conductivity of the interior of the Moon was halved (0.005 in place of 0.01), this thickness changed to 200 to 400 km (refs. 1 and 8). Seismic observations have shown that the thickness of the outer solid layer is about 1000 km (ref. 16), i.e., at present only about 20 percent of the volume of the Moon is partially molten.

This direct determination of the partially melted state of the central area of the Moon has great significance, since it confirms the correctness of using conductive models in calculating its thermal history. In convective models, which consider stable thermal convective models, which consider stable themal convection in solid matter, it is found that the interior of the Moon should be solid right to its center (refs. 29, 30, and 31). It would be surprising if the convective models were confirmed, since they make the quite unrealistic implicit assumption of chemical homogeneity of the mantle of the Moon. After general differentiation leading to the separation of the crust, the matter remaining in the mantle should also be somewhat differentiated. At the same time, a very slight concentration of the heavier substances toward the center is sufficient to completely prevent thermal convection. Now that the presence of the partially molten "core" of the Moon has been established by direct seismic observations, we can quite justifiably use conductive models of the Moon in the study of its thermal history.

THE HEAT FLUX AND THE CONTENT OF RADIOACTIVE ELEMENTS NECESSARY TO PROVIDE IT

Measurements of the heat flow at the landing sites of Apollo 15 and 17 (refs. 32 and 33) have shown that it amounts to 28–30 erg/cm^2 s, i.e., about 0.7×10^{-6} cal/cm^2 s; whereas the models with chondritic radioactivity give 10–20 erg/cm^2 s, i.e., $(0.25–0.45) \times 10^{-6}$ cal/cm^2 s (refs. 6, 7, and 8) (see also refs. 4 and 5). At the same time, chondritic models yield a satisfactory picture of the Earth's thermal history (ref. 34). If the heat flow measured at two points on the lunar surface is typical for the entire Moon, then in order to explain it we must assume an average generation of radiogenic heat per unit of mass approximately three times greater than in the chondritic meteorites (refs. 13, 15, and 33). The results of Troitskiy indicate it is valid to extrapolate the heat flow measured at only two surface points to the entire Moon. Based on his measurements of thermal radio radiation from the entire visible hemisphere of the Moon, he obtained almost the same value of heat flow $(0.85 \pm 0.2) \times 10^{-6}$ cal/cm^2 s = 35 erg/cm^2 s (ref. 36)[2].

[2] The numerical value of heat flow depends on the value of parameter $\gamma = (k\rho c)^{-1/2}$, determined from the same radio observations. Using the value $\gamma = 600$, Troitskiy obtained a value of heat flow of $(1.0 \pm 0.3) \times 10^{-6}$ cal/cm^2 s (refs. 35 and 36). Later, using $\gamma = 700$, he obtained the value of heat flow presented in the text. Using the same measurements, Linsky (ref. 37) used $\gamma = 1300$ to determine a significantly lowed flow of 0.34×10^{-6} cal/cm^2 s near the flow obtained in calculations for chondritic models. However, Troitskiy (ref. 36) stands by his high value of heat flow. In a report at the Kiev Symposium (1968), he presented the following limits for heat flow, based on two models of the structure of the surface layer: from 0.7×10^{-6} to 0.95×10^{-6} cal/cm^2 s (ref. 38).

Nevertheless, the situation with heat flow remains unclear. On the one hand, suspicions exist that the thickness of the crust is twice as great on the back side of the Moon as on the visible side. (This would explain the shift of the center of the geometric figure of the Moon relative to its center of mass.) If the content of radioactive elements in the crust were uniform, the heat flow on the back side of the Moon would be even greater than on the front side. On the other hand, in the outermost layer of the Moon there are significant regional differences in the content of radioactive elements. Therefore, we cannot as yet eliminate the possibility that the large heat flows measured at the landing sites of Apollo 15 and 17 are local anomalies.

If we discard these doubts and consider the measured heat flow to be typical for the entire Moon, this is a new "boundary condition" that must be satisfied by calculations of the thermal history of the Moon. This condition restricts the present-day release of heat in the Moon's interior to very narrow limits. It must be three times greater than in the chondritic meteorites and also, apparently, in the Earth. Consequently, the long-lived radioactive elements, or at least some of them, must be present in the Moon in larger quantities than in meteorites and in the Earth. Although cosmochemists have set forth some ideas about this (see section titled "Proposed Differences in the Chemical Composition of the Earth and the Moon"), there is no cosmochemical foundation for these differences.

Model of the Moon's Thermal History Satisfying the New, Present Day–"Boundary Conditions"

Until recently, the present thickness of the outer solid layer of the Moon was determined by calculations of the thermal history or on the basis of the electrical conductivity profiles, which were nonuniquely determined from magnetic measurements. The thickness of the outer solid layer is now a reliable "boundary condition," known from seismic observations on the Moon.

If we consider the measured values typical for the entire Moon, we can use the heat flow from the interior as a second new boundary condition.

The measured heat flow requires the generation of approximately three times more heat in the Moon than in chondritic meteorites and, at the same time, the thickness of the outer solid layer has been found to be two- to four-times greater than that calculated for the chondritic models that had seemed most probable. Insofar as a large generation of heat hinders the cooling of the outer layers, it seems useful to calculate models of the lunar thermal history that satisfy both of the new boundary conditions.

The calculations of Toksöz and his colleagues (refs. 13, 14, and 15) were performed before seismic observations were used to determine the thickness of the solid layer. The main purpose of these calculations was to estimate the content of radioactive elements necessary to explain the measured heat flow. However, the current thickness of the solid layer in the models of these authors is half the true thickness. Furthermore, these authors utilize an initial temperature distribution with hot outer layers and cold interiors, in accordance with the first attempts to interpret the composition of lunar specimens. At the present time, this initial distribution of temperature is required only if we assume heterogeneous accumulation of the Moon. However, this assumption is not confirmed by a number of petrological and chemical properties of the lunar specimens (ref. 39) and, furthermore, does not agree with cosmogonic data, i.e., with the existing hypotheses for the origin of the Moon.

We have considered a simplified conductive model covering the last 3.5×10^9 yr of thermal history of the Moon and capable of giving an estimate of the distribution of radioactivity of the elements between the crust and mantle, as well as an estimate of the degree of partial fusion of the interior 3.5×10^9 yr ago. The complex and poorly known thermal evolution of the Moon for the first 1 × 10^9 years of its existence was not studied. It was assumed that during this early period the interior of the Moon was subject to partial melting and magmatic differentiation due to the high initial temperature. As a result, the Moon was divided into a 63-km-thick homogeneous crust rich in radioactive elements and a homogeneous mantle poor in these elements. Then, the next 3.5 × 10^9 yr of the thermal history of this two-layer model were studied. During this entire time the model cools because the heat liberated in the crust can be easily lost into space. At the same time, this cooling occurs slowly since, as earlier calculations for differentiated chondritic models have shown (ref. 8), the heat flux through the surface is only 10- to 30-percent (depending on the model) greater than the equilibrium flow that corresponds to an equality between heat generation in the entire Moon and the total flux through the surface.

Since we were studying material that had already experienced differentiation in the interior, the temperature interval of melting was assumed to be 100°. The effective heat capacity was taken for this interval, considering the heat of fusion. Here, as before, we used a "triangular" dependence for the additional heat capacity with temperature (ref. 7).

The liquidus of anhydrous basalt (ref. 40) used was as the temperature of total melting, whereas in earlier calculations we used the old data of Wolf for the pressure-dependence of the melting point of dunite, which yields a smaller difference in melting temperatures between the center of the Moon and the surface.

The thermal conductivity of the lunar mantle and crust was taken as the sum of conductive and radiative thermal conductivities. However, the latter is of secondary importance, even at $\varepsilon = 10^{-1}$, since temperatures in the Moon are comparatively low.

The following "initial" temperature distribution was used: it was assumed that in the interior the temperature 3.5 × 10^9 yr. ago was 10 to 20° higher than the solidus temperature. With the "triangular approximation" of additional heat capacity, this corresponds to 2 to 8 percent of melted material. In the outer 200 km or so, the initial temperature dropped smoothly to the surface (more precisely speaking, to the subsurface) temperature of 230K in the equatorial zone and 90K at the poles.

In our calculations, we sought a combination of parameters to satisfy the following boundary conditions: the current thickness of the outer solid layer is about 1000 km, and the heat flux is about 30 erg/cm² s. One of the satisfactory combinations of parameters is presented in table 1. In this model, the content of uranium and thorium in the Moon's crust is nine times greater than the mean; in the mantle it is 19 times less than the mean. Thus, some 95 percent of the total quantity of these elements is concentrated in the crust. The crust also contains 90 percent of the potassium. It is assumed that 3.5 b.y. ago the temperature of the interior below 200 km depth was 20° higher than the temperature of the beginning of melting. In our model, this means that about 8 percent of the matter was melted at each point in the internal area.

As we can see from figure 1, the curve for the present-day temperature intersects the solidus curve at a very small angle, penetrating slightly into the temperature interval for

Table 1.—*Numerical Values of Parameters for One of the Satisfactory Models*

Crusted thickness	63 km
Heat capacity	0.25 cal/g • deg
Heat of melting	100 cal/g
Melting interval	100°
Heat conductivity at 0° C	0.01 cal/cm • s • deg
Opacity	10 cm^{-1}
Surface temperature	
at the equator	230K
at the poles	90K
Content of radioactive elements:	

(Th/U = 4)

	U (10^{-8} g/g)	K (10^{-4} g/g)	K/U
Mean	6.62	1.75	2 650
In crust	60	15	2 500
In mantle	0.35	0.34	10 000

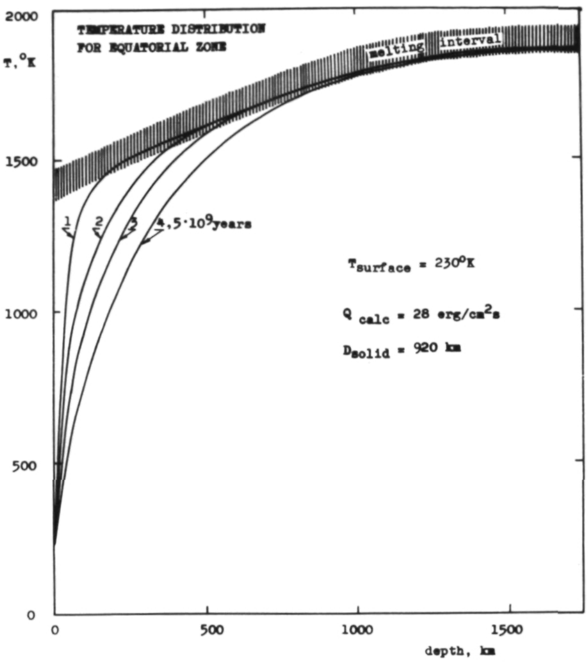

Figure 1.—*Distribution of temperature along radius for equatorial zone. Age of Moon assumed 4.5 × 10⁹ yr, so that t = 4.5 × 10⁹ corresponds to the present time. The curve for t = 1 × 10⁹ illustrates the assumed "initial" temperature.*

partial melting. Thus, the boundary between the solid and partially melted areas of the lunar interior may be very vague. This probably corresponds to the great thickness of the layer where deep earthquakes originate on the Moon. With such a small angle between curves, the observed thickness of the solid layer determines the acceptable combination of parameters with great accuracy. An example in which the content of radioactive elements in the mantle is varied slightly is shown in figure 2.

The surface temperature in the polar areas of the Moon is significantly lower than in the equatorial areas. Therefore, as has already been shown in our earlier calculations of the thermal history for chondritic models of the Moon (refs. 6, 7, and 8), the thickness of the outer solid layer, as well as the heat flow, is greater in the polar areas than in the equatorial area (fig. 3). As a result, the central, partially molten area has a flattened, not a spherical, shape (fig. 4)[3]. Thus, the hypothesis of Levin, which attributes the flattening of the dynamic figure of the Moon to a decrease in surface temperature from the equator to the poles (refs. 4, 39, and 41), remains in force.

Our calculations show that if we start with an early melting of the Moon (i.e., a high initial temperature) and a high content of radioactive elements in the Moon, its modern thermal properties are explained without difficulty. However, both of these assumptions are riddles, related to the as yet unknown origin of the Moon.

Proposed Differences in the Chemical Composition of the Earth and the Moon

Many students of the Moon consider that in addition to different contents of radioactive elements shown by the high heat flux

[3] It is possible that the partially molten central area is not a spheroidal, but has a more complex form.

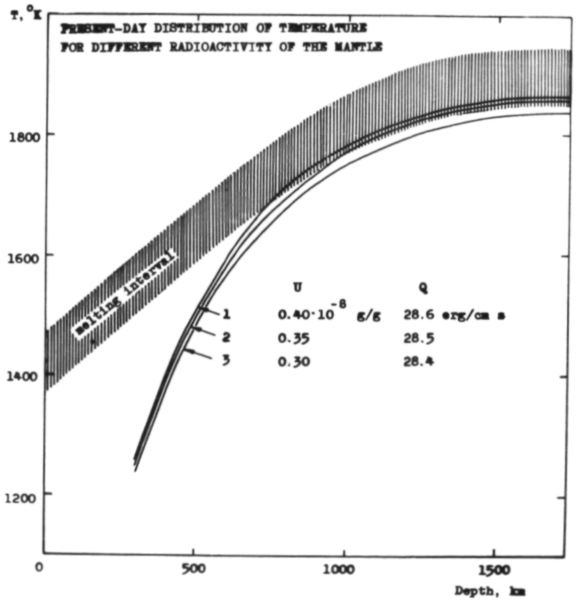

Figure 2.—*Current distribution of temperature with various contents of uranium and thorium in the mantle (Th/U = 4; content of potassium as shown in table 1).*

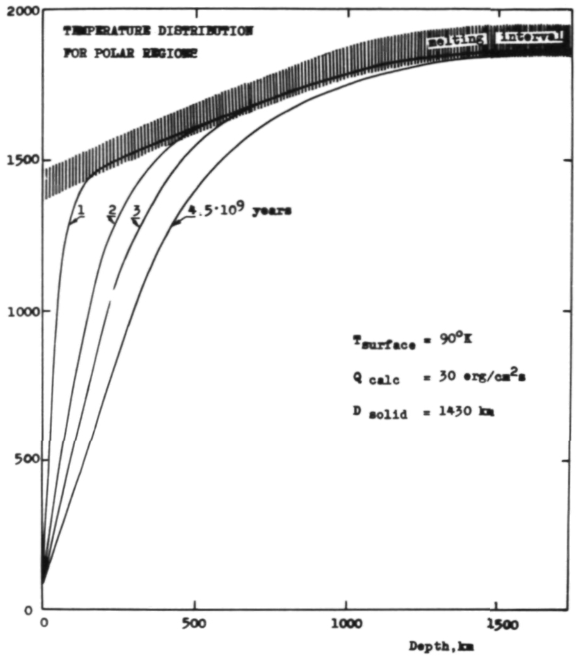

Figure 3.—*Distribution of temperature along radius for polar areas.*

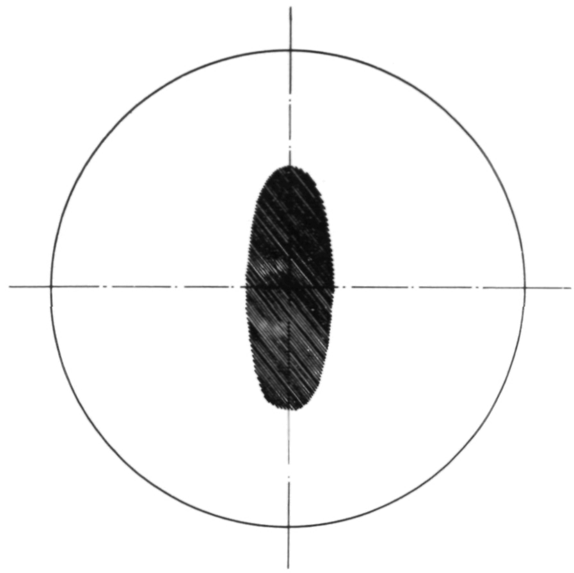

Figure 4.—*Schematic cross section of the Moon. Central partially molten area shaded.*

of the Moon there are differences in the chemical composition of the Earth and Moon as well: a different content of iron; a shortage of volatile elements in the Moon; enrichment of the Moon with calcium and aluminum. However, none of these differences has been firmly established.

Based on analyses of a limited number of lunar samples taken at a small number of points on the surface and, in addition, distorted by processes accompanying the impact of bodies that have struck the Moon, it is a bit early yet to speak of impoverishment or enrichment of the entire Moon with various elements. It is particularly early to utilize these assumed impoverishments or enrichments as a basis for judgments about the origin of the Moon. Even the question as to how magmatic differentiation of the Moon occurred is a subject of intensive debate (e.g., see refs. 11, 18, 43, and 44). Apparently, Biggar et al. (ref. 43) are correct in stating that the "shadowing effect of near-surface processes, which have changed the composition of the lunar rock, prevents us from placing realistic limitations on the nature of the lunar interior, except for those already established on the basis of astronomical data. It is as yet impossible, on the basis of petrological or chemical data, to make a firm selection between formation of the Moon by separation at an early stage, capture or joint formation."

Silver, in his report to the seventh working group of COSPAR (April 1973), decisively rejected the possibility of judging the composition of the entire Moon on the basis of samples of surface rock currently available.

It is probably not by chance that the summary of the scientific results of the fourth conference on lunar science (March 1973), written by the Lunar Sample Analyses Team (ref. 32), contains no mention of the possible composition of the entire Moon or of its enrichment or impoverishment with various elements and compounds.

The authors of the present report are not competent to judge chemical and petrological data. We will limit ourselves to a few examples and comments.

DIFFERENCES IN IRON CONTENT

Since the dimensionless moment of inertia of the Moon, in spite of its light crust, is quite close to 0.4, it does not contain even a small iron core whose presence would be permissible from its low mean density (refs. 45 and 46). At present, no one doubts that the interior of the Moon has been subjected to magmatic and gravitational differentiation and, therefore, if there were any metallic iron alloy it would have sunk to form a core. If we accept the latest value of dimensionless moment of inertia (ref. 32), the mass of the

$$C/Mr^2 = 0.395 \begin{matrix} +0.005 \\ -0.010 \end{matrix}$$

iron core, if there is one, is not over 1 to 2 percent of the mass of the Moon.

Consequently, if we do assume that the Earth has an iron core, we reach the unavoidable conclusion that there is a significant difference in the content of iron in the Earth and in the Moon. However, one of the authors of the present report (Levin) remains a "heretic" and continues to prefer the hypothesis of a metalized core for the Earth (refs. 47 and 48). In this case, the Earth and Moon might have a similar or even identical iron content.

DEFICIENCIES OF VOLATILE ELEMENTS

Based on the depletion of volatile elements in the lunar basalts in comparison to analogous terrestrial basalts, some researchers believe that the entire Moon is poor in volatile elements, including such heavy elements as lead, bismuth, and thalium (refs. 49, 50, 51, and subsequent works). However, the history of thalium analyses can serve as an example of the dangers related to the insufficient number and variety of lunar samples.

All samples returned by Apollo 11, 12, and 14, which landed in mare areas of the lunar surface, were deficient in thalium. However, some of the anorthosite samples returned by Apollo 15 were found to be rich in thalium, and the majority of the anorthosites returned by Apollo 16 were rich in thalium (refs. 52 and 53).

One striking example of the sharply differing opinions is the debate concerning the origin of the mare basalts. Ringwood and his colleagues consider them to be a direct product of partial melting of the substance of the interior (refs. 54 and 55), whereas the English petrologists present them as supposedly convincing proof that the lunar mare were at one time lava lakes in which fractional crystallization occurred (ref. 43). They do not ascribe the deficit of volatile elements to a depletion of these elements in the whole Moon, but explain it by selective volatilization from hot lava issuing onto the surface, or, significantly more effective, from fire fountains accompanying the eruption of lava.

If we view the depletion of volatiles in the lunar basalts as a manifestation of an overall depletion throughout the Moon and attribute it to the accumulation of the Moon from matter that was still hot and condensing in the cooling protoplanetary cloud, Anders and his colleagues have found that the temperature of this matter must have been about 620K. However, since the duration of accumulation of the condensing matter could not have been much less than the duration of cooling of the cloud, the Moon, like the other bodies of the terrestrial planets, should consist of a mixture of matter that condensed at different temperatures, including low temperatures. Therefore, the meaning of the condensation temperature for lunar material found by Anders and his colleagues is not clear. Furthermore, these authors assume equilibrium condensation, whereas, as Arrhenius and Doe have recently shown (ref. 56), the conditions in the cloud must have been far from equilibrium, and condensation must have occurred with the temperature of dust particles much lower than the temperatures of the gas.

In all of the rocks returned from the surface of the Moon, the ratio of potassium to uranium is less than in terrestrial rocks and much less than in the meteorites. However, both Urey (ref. 57) and Arnold (ref. 58) refrain from extrapolating this difference to the entire Moon. As Arnold notes, it is still not clear whether the loss of potassium occurred before the formation of the Moon, during its formation, or after its formation.

While emphasizing the absence of water in most lunar rocks, Urey (ref. 59) noted that at the Apollo 17 site some rocks contain volatiles which, in his opinion, might indicate the presence of volatiles in the deeper rocks of the Moon.

Thus, the entire range of questions related to the depletion of volatiles requires further investigation.

ENRICHMENT OF THE MOON WITH MINERALS RICH IN CALCIUM AND ALUMINUM

Since the continental areas of the Moon, which represent the greatest portion of its surface, consist of anorthositic rocks, there is no doubt as to the enrichment of the surface layers with minerals rich in Ca and Al. However, it is debatable to what extent this composition of the surface rocks indicates enrichment of the entire Moon with such minerals. These minerals, which are "early condensates" (see below) according to the theory of equilibrium condensation, are encountered as inclusions in the Allende meteorite and other type II and III carbonaceous chondrites.

Ringwood and Essene (ref. 55) proposed that the content of these minerals on the Moon was higher than that on Earth, but still moderate (~ 0.2 by mass). They considered that a higher content in the lunar interior would, as a result of their conversion into denser phases, cause a high mean density of the Moon, which does not agree with the observed density. Anderson (refs. 60, 61, and 62) proposes that the Moon consists almost entirely of these minerals and presents arguments (refs. 62 and 63) in favor of rejecting the limitations set forth by Ringwood and Essene. He bases his conclusions on the argument of Gast (ref. 64) who believed that the enrichment of the surface rock of the Moon with Ca and Al indicates enrichment of the source of this rock in these elements, i.e., enrichment of the interior. Wanke et al. (refs. 65 and 66) consider that the Moon consists of a mixture of matter similar to the inclusions in the Allende meteorite, plus the matter of the chondritic meteorites. Assuming that the ratio of potassium to lanthanum in the lunar samples is typical for the entire Moon and using their analyses of inclusions from Allende, they found that the content of matter similar to these inclusions amounts to 69 percent in the Moon, whereas in the Earth its content is found to be 22 percent, based on the same calculation. At the same time, Anders and his colleagues made similar calculations using not two, but five phases and found that the Moon contains 42 percent of material similar to the Allende (ref. 53) inclusions.

All of the above authors consider the minerals rich in calcium and aluminum to be "early condensates." Indeed, according to the theory of equilibrium condensation in a cooling protoplanetary cloud of solar composition, assuming identical temperatures for dust particles and gas, these minerals should condense at temperatures above 1300K, i.e., before iron and silicates (ref. 67). This is seemingly confirmed by Grey et al. (ref 68) who found that the Ca- and Al-rich chondrules from the Allende meteorite have the most primitive strontium isotopic composition known.

It should be noted that according to the theory of equilibrium condensation, uranium and thorium should be incorporated in the early condensates. This is confirmed by the high uranium content in the Allende inclusions (refs. 65 and 66). Due to this, in spite of the depletion of potassium, the total heat production in the early condensates is found to be greater than in chondritic material. Thus, the enrichment of the Moon with early condensates might explain the high heat flux from its interior.

However, the protoplanetary disk should have been transparent for infrared radiation and, therefore, as Arrhenius and Doe have shown (ref. 56), the temperature of dust particles should have been hundreds of degrees or even a thousand degrees lower than the kinetic temperature of the gas. For many compounds, this does not change their sequence of condensation; but for some compounds, it makes a significant difference. Apparently, the course is that the hot gas should have been partially ionized, and in this case ionization potentials begin to play a role. According to Arrhenius (ref. 69), minerals rich in Ca and Al would condense at lower temperatures under these conditions, i.e. after iron and the silicates.

Onuma et al. (ref. 70) measured the differences in the isotopic composition of oxygen in terrestrial, lunar, and meteoritic specimens and interpreted them as the result of physical and chemical processes occurring at different temperatures. They considered that their measurements confirmed that the Ca- and Al-rich minerals from the Allende meteorite are actually high-temperature condensates. However, further measurements (ref. 71) have led to the conclusion that the peculiarities of the isotopic composition of oxygen in the carbonaceous chondrites are related not to chemical reactions but rather to the presence of an admixture of some "primitive" component (perhaps interstellar dust) very poor in O^{18} and O^{17}. Therefore, although it is impossible to determine the formation temperature of these inclusions, the presence of this admixture, like the results of Grey et al. (ref. 68) speaks against the conclusions of Arrhenius and in favor of the idea that the inclusions from Allende are not only early condensates, but also early "accumulates."

We know of two attempts—in our opinion unsuccessful—to explain the enrichment of the entire Moon with minerals rich in calcium and aluminum.

Anderson (refs. 60 and 61) proposed that the Moon consists almost entirely of early condensates and, therefore, differs greatly from the Earth. He also attempted to explain this difference by referring to the dependence of condensation temperature on pressure. He assumed that in contrast to the Earth, which accumulated near the central plane of the protoplanetary cloud, the Moon was somehow accumulated at some distance from this plane under lower pressure conditions. As a result of this, for some reason, the Moon includes only substances that condense before iron. Just exactly why remains unclear. Furthermore, the hypothesis of Anderson contradicts the laws of celestial mechanics, both for formation in circumsolar orbit significantly inclined to the ecliptic, and for formation in circumterrestrial orbit, even if perpendicular to the ecliptic. Twice in each revolution, the Moon would have to intersect the central plane of the protoplanetary cloud or the circumterrestrial swarm, and it is here, in the layer of maximum density of solid matter, that its main accumulation should occur. Later, Anderson (ref. 63) published a more detailed foundation for his idea that the Moon might consist entirely of early condensates, but the authors of the present report are unable to understand either his explanations as to where and how this might occur (ref. 65) or his answer (sec. 12, p. 56) to the objections of Cameron (ref. 72). Cameron himself, accepting the composition of the Moon according to Anderson, assumes that it was formed within the orbit of Mercury and later captured by the Earth. We also disagree with this hypothesis, since capture from an orbit differing greatly from the orbit of the Earth is practically impossible (see below).

Returning to the ideas of Anderson, we should note that he accepts the hypothesis of "accumulation during condensation," i.e., assumes that accumulation somehow occurred more rapidly than the cooling of the protoplanetary cloud. At the same time, he rejects the hypothesis of heterogeneous accumulation, preferring the idea of homogeneous initial lunar composition. True, he notes that the chemical stratification of the Moon, arising in his opinion as a result of early differentiation, is practically indistinguishable from that which would occur with heterogeneous accumulation.

Anders and his colleagues (ref. 53), considering that the moon contains 42 percent "early condensates," whereas the Earth contains only 6 percent of these condensates according to their calculations, explain this by stating that the formation of the Earth and the Moon began with the formation of small "nuclei" consisting only of "early condensates" with masses of 6.3 percent and 0.5 percent of the contemporary mass of the Earth, respectively. Further accumulation of later condensates, namely chondrite-type condensates containing iron, increased the mass of the terrestrial protobody by a factor of 15, but the mass of the lunar protobody probably by only two times, leading to their variation in content of early condensates. Thus, it is implicitly assumed that by the moment of condensation of chondritic-type matter, all of the early condensates were already incorporated in the protobodies of the Earth and Moon, which were the only large bodies in the "Earth zone" of the protoplanetary cloud. However, the presumed cooling of the protoplanetary cloud should have occurred more rapidly than the accumulation of the condensation products, and, furthermore, the formation of the protobodies of the Earth and Moon should have been accompanied by the formation of many other bodies of similar dimensions and composition, later to be absorbed by the Earth and Moon. If they, as Anders and his colleagues believe, consisted of early condensates, their incorporation into the growing Earth and Moon during the stage of accumulation of chondritic matter would have continued to increase the content of early condensates in the Earth and Moon.

It must be added that Anders and his colleagues refer to the calculations of Öpik, who used a greatly simplified model to illustrate the differences in growth rate of two protobodies of different mass in similar orbits around the Sun. Thus, they implicitly refer to the point of view of the formation of the Moon by capture.

At the present time, it seems premature to attempt to determine the origin of the Moon on the basis of its proposed enrichment with minerals rich in Ca and Al. First we must determine whether any such enrichment actually exists and how great it is. We must better determine the mean thickness of the anorthosite layer for the entire Moon and the mechanism of its formation during the course of magmatic differentiation of the Moon. Only after this can we make any reliable judgment about the content of these minerals in the mantle of the Moon, which makes up 90 percent of the Moon's substance.

At the same time, we should turn our attention to clarification of the question of possible conditions of formation for these minerals—are they early or late condensates and are there still other ways to form them?

Origin of the Moon

At present, as before the beginning of direct investigation of the Moon, three main hypotheses of its origin continue to be discussed: (1) fission of the Moon from the Earth, (2) the capture hypothesis, and (3) the joint formation of the Earth and the Moon. The hypothesis of Öpik (ref. 57) recently appeared and combines the capture hypothesis with the hypothesis of the Moon's accumulation in the vicinity of the Earth.

Unfortunately, the new data on the Moon mentioned in the preceding sections of our report only increase the difficulties which stand before any attempt to explain its origin.

THE FISSION HYPOTHESIS

As was the case a few years ago, the hypothesis of fission of the Moon from the Earth remains without any mechanical foundation (ref. 1). The problem is not only that the calculations of past tidal evolution of the Moon indicate that the plane of the lunar orbit has never coincided with the plane of the Earth's equator; not only that the current total momentum of the Earth-Moon system is insufficient for rotational separation of an initially single body; and not only that a satellite which separated from the Earth, within the Roche limit, would have been destroyed by tidal forces. But, as has been demonstrated by Lyapunov (ref. 73), Cartan, (refs. 74 and 75), and Littleton (refs. 76 and 77), even if rotational instability devolops, *smooth* separation of a satellite would be impossible. The onset of rotational instability leads not to separation, but rather to ejection of some of the material. If the ejection velocity were greater than the parabolic velocity, the material would depart forever. If it were less than the parabolic velocity, it would fall back to Earth. In the latter case, the ideal case, these ejections and returns would be repeated over and over forever. However, the return fall, occurring at high relative velocity, would be accompanied by explosive ejection of matter, and some of the clumps or "spray" would achieve hyperbolic velocities and, therefore, carry away the excess moment creating the rotational instability.

Fission hypotheses continue to be discussed in connection with the problem of the origin of close binary stars. In this case, in contrast to the problem of the Earth and the Moon, we are studying not idealized bodies of homogeneous density with solid-body rotation, but rather bodies of compressible gas which, therefore, have sharply increasing densities toward the center and, furthermore, not necessarily bodies with solid-body rotation. However, 20 years ago Littleton (ref. 74) believed that with centrally condensed bodies the situation is still worse than with homogeneous bodies. As we can see from the articles of Ostriker (ref. 78) and Leboviz (ref. 79), the possibility of fission of such bodies still remains hypothetical. It should be noted that the proponents of the fission of centrally condensed bodies limit themselves to discussion of the conditions for the onset of instability, without analyzing the question of to what this instability would lead, i.e., without studying the actual process of the supposed separation.

At first glance, the idea of the fission of the outer layers of the already differentiated Earth is attractive in that it could explain some of the supposed differences in the composition of the Earth and the Moon (refs. 80 and 81). However, we should not be misled by this, since contradictions would then arise with other geochemical data. For example, as Wanke believes (ref. 65), the difference in the values of the FeO/MnO ratio on Earth and on the Moon contradicts the hypothesis of separation of the Moon from the Earth. Furthermore, a contradiction would arise in geophysical data as well. The Moon and the Earth were formed practically simultaneously some 4.6×10^9 yr ago. If we assume that the Earth was already differentiated at the moment of separation from the Moon, we must assume a hot initial state, which is incompatible not only with the solid contemporary state of the entire mantle, but also with the small thickness of the terrestrial crust, indicating that it is a product of differentiation only of the upper mantle.

THE CAPTURE HYPOTHESIS

In its usual form, the capture hypothesis assumes the capture of the already formed Moon as a result of tidal friction during a close passage. However, this friction is so small that in order for capture to have occurred it is necessary that the geocentric orbit of the Moon before capture differ negligibly from a parabolic orbit, in order that its "velocity at infinity" be almost zero. This means that the probability of such a capture is negligible. Furthermore, this means that before capture the Moon must have moved around the Sun in an orbit almost identical to that of the Earth. Therefore, it is incorrect to think that the capture hypothesis provides a means of explaining the assumed differences in the composition of the Earth and the Moon, for example by allowing the formation of the Moon at some distance from the Earth, such as in the zone of the asteroids or within the orbit of Mercury, as Cameron suggests (ref. 72). Actually, the capture hypothesis requires formation of the Moon in the zone of formation of the Earth.

As Öpik has shown (ref. 57), the most probable form of capture of the Moon is capture of a portion of the matter of a large body broken off by tidal forces during passage (again also on a nearly parabolic geocentric orbit) within the Roche limit. Fragments of the hemisphere turned toward the Earth are captured, according to Öpik, in elliptical geocentric orbits, while fragments of the opposite hemisphere fly away, carrying with them a portion of the energy and moment of the captured fragments, as would be required for capture. If the fragments formed an absolutely homogeneous ring, tidal evolution would be impossible. However, unavoidable fluctuations in the distribution of the fragments around the Earth would result in tidal interaction with the Earth and their movement out beyond the Roche limit, where they would be combined into one or a few bodies. Thus, the hypothesis of Öpik combines the capture hypothesis with the hypothesis of accumulation of the Moon in the vicinity of the Earth.

A single body of lunar mass, if one could be present within the Roche limit, would move out beyond this limit in 5 years. If there were 1000 identical fragments with the same total mass, according to Öpik they would take thousands or tens of thousands of years to move out beyond the Roche limit.[1] However, if we consider that collisions between these fragments, occurring while still within the Roche limit, should be accompanied by fragmentation, i.e., increases in the total number, the time of movement to beyond the Roche limit would probably be still greater. Therefore, although the fragments should combine rapidly once beyond the Roche limit, the time of accumulation of a single Moon would be greater than 10^2 to 10^3 yr, the time necessary for its heating by gravitational energy. However, Öpik assumes the possibility of formation of several, for example, six, protomoons, whose later combination into a single Moon could result in its hot state.

Thus, Öpik's hypothesis about the formation of the Moon from fragments of a relatively large body captured by the Earth during passage within the Roche limit, with the resulting breakup by tidal forces, opens some possibilities for explanation of the high initial temperature of the Moon that are worthy of further study. However, this brings up many mechanical diffculties. Furthermore, as in the capture hypothesis for an already formed Moon, we are concerned here with the capture of a portion of the matter of a body moving in a *near-terrestrial orbit* and we do not as yet see any cosmogonically well-founded means for explaining the assumed (but as yet unproven) differences in composition between the Earth and the Moon.

THE HYPOTHESIS OF JOINT FORMATION OF THE EARTH AND MOON

According to the hypothesis suggested by Schmidt (refs. 82, 83, and 84), the Moon (as well as the regular satellites of the other planets) was accumulated in the vicinity of the growing Earth from the *circumterrestrial* swarm of bodies and particles, which was continually supplemented during the accumulation of the Earth from the *circumsolar* swarm of bodies and particles. According to this hypothesis, the formation of the Moon is a byproduct of the process of formation of the Earth.

In the vicinity of the growing Earth, inelastic collisions of bodies moving in circumsolar orbits had to occur. A certain fraction of the fragments then took on orbits around the Earth, i.e., formed a sparce circumterrestrial swarm. The particles of this swarm accumulated rapidly into the protomoon, but as long as rather intensive accumulation of the Earth continued, the existence of the circumterrestrial swarm was maintained by new collisions in the vicinity of the Earth.

The hypothesis of Schmidt is based on processes that must have occurred in the course of accumulation of the Earth, and it is most promising from the mechanical standpoint (ref. 85). Attempts at quantitative development of this hypothesis are contained in a number of papers by Ruskol

[1] In his preceding works, Öpik considered that the time of movement was proportional to the square root of the number of bodies (of identical mass). In his work of 1972, he indicated that this was an error and that actually it was directly proportional to the number of bodies.

(refs. 39, 86, 87, and 88). Unfortunately, new data on the Moon, its hot initial state, and possible differences in the composition of the Earth and Moon, might be a stumbling block for this hypothesis.

Actually, if the accumulation time of the Moon was as long as that of the Earth, the gravitational energy of accumulation, liberated primarily on the surface, would have been radiated out into space and could not have significantly increased the initial temperature of the Moon. As was noted earlier (ref. 1), the existence of a temporarily dust-filled atmosphere around the Moon during its accumulation might have prevented strong radiation and resulted in heating of the interior due to gravitational energy. However, if the greenhouse effect of the dusty atmosphere was so strong on the Moon, we would expect no less of a greenhouse effect on Earth, which leads to serious contradictions with our ideas concerning the thermal history of the Earth.

Ten years ago, MacDonald (ref. 89) wanted to lengthen the time scale for tidal evolution of the Moon and set forth the idea that in the past there were several protomoons around the Earth, which later combined into the contemporary Moon. Recently, Ruskol (ref. 90) attempted to apply the idea of several protomoons to explain the high initial temperature of the Moon. Actually, the merging of two or three protomoons might, if all of the gravitational energy were retained, result in significant heating of the interior. However, retention of the energy would require an almost head-on collision.

The possibility of early heating of the Moon by tidal deformations depends on the poorly known initial dynamic properties of the Earth-Moon system. The initial ellipticity of the lunar orbit is very important here. According to Alexander (ref. 91), this ellipticity in the past was not great, indicating that further studies in this direction are promising.

With a longer accumulation time for the Moon, as follows from the hypothesis of Schmidt, the liberation of energy by short-lived radioactive elements (if they were initially present) and electromagnetic heating by the intensive corpuscular radiation of the young Sun (if it passed through a T Tauri stage) should be significantly weakened or practically ended before the completion of formation of the Moon. These sources of energy could hardly have played a significant role in the initial heating of the lunar interior.

Within the framework of the hypothesis of Schmidt concerning the common formation of the Earth and Moon, it is natural to expect identical compositions for the Earth and Moon. The attempt by Ruskol (refs. 92 and 93) to prove that this hypothesis leads to a different composition of the two bodies seems dubious, both as concerns attempts to explain the supposed deficit of volatiles in the Moon, and as concerns attempts to explain the absence of an iron core in the Moon.

Ruskol attributes the depletion of volatiles to the fact that particles captured in the circumterrestrial swarm must have experienced an additional collision, the collision which caused their capture, in comparison to circumsolar particles which were directly included in the composition of the Earth. However, we are speaking here of a single additional collision, which could hardly have produced a significant effect. Furthermore, as Ruskol herself proved (ref. 93), it is possible that the Earth was also accumulated to a significant extent from particles that had been present in the circumterrestrial swarm.

Ruskol, following the idea of Orowan (ref. 94), attributes the absence of a lunar iron core to differences in the plastic properties of stony and iron particles. This difference should truly have played a role in the accumulation of tiny particles, however even the sign of the effect is unclear (ref. 95). However, in the gravitational accumulation of bodies hundreds of kilometers in diameter, the plastic properties of the particles should lose their meaning. Actually, it is this stage of accumulation that is most important, i.e., longest, in the formation of bodies of lunar and larger dimensions. Ruskol starts from the physically unjustified assumption of linear growth of iron content, and therefore of density, as a function of the logarithm of the radius of a body in the range from 10^{-4} to 10^{8} cm. Therefore, her explanation of differences in the content of iron in the Earth and the Moon is purely formal.

We should once more emphasize that the hypothesis of Schmidt does not assume that a swarm sometimes existed around the Earth, and contained the entire mass of the contemporary Moon. But, if it did exist, then it is not difficult to show that its accumulation into one or a few large bodies would require less than 100 years. Consequently, the formation of such a swarm should have lasted at a maximum a few years, i.e., should have been practically instantaneous. Apparently, the only method capable of explaining such a "quasi-instantaneous" development of the circumterrestrial swarm is a collision of two comparatively large bodies (with total mass much greater than the mass of the Moon) moving in circumsolar orbits in the vicinity of the Earth. It is possible in principle that upon such a collision some of the fragments, with mass equal to the mass of the Moon, remained in circumterrestrial orbits. The accumulation of a swarm that developed in this manner into a single body should require no more than a few decades and would lead to heating of the Moon by gravitational energy. In addition to explaining the high initial temperature of the Moon, this method of formation also opens a path to explanation of the differences in the composition of the Earth and the Moon (if they are confirmed). The bodies whose collision generated the circumterrestrial swarm may have been formed at distances from the Sun differing somewhat from the distance at which the Earth was formed. In case of a significant dependence of the composition of a body on its distance from the Sun during its formation, we could attempt to explain in this manner those differences in the composition of the Earth and the Moon which will be established by future studies.

As we can see from the above, establishment of the high initial temperature of the Moon has not helped to explain its origin. Quite the opposite, attempts to explain the new data on the Moon bring up new and serious difficulties and riddles. Many of these riddles are made worse by the fact that attempts to solve lunar problems must be correlated with the explanation of the origin of the other planetary bodies in the solar system. Only in this manner can we avoid exaggerating the importance of ad hoc hypotheses and move forward to a proper understanding of the origin of the entire solar system.

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