

Dynamic Model for the Formation of the Earth-Moon System

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Abstract—Some geochemical characteristics of the Moon are such that they contradict the hypothesis of the Moon's formation from the Earth's mantle. We propose a new alternative to the currently accepted giant impact hypothesis. It was shown that 40% evaporation of a material of chondritic chemistry yields a composition similar to that of the Moon, including low iron content. It is known that evaporation is accompanied by isotope fractionation, whereas no isotope effects were detected in lunar soils within the analytical accuracy. However, isotope fractionation can be absent, if matter evaporates under equilibrium conditions. Such conditions occur in a cloud of hot particles. In order to justify this concept, we developed a computer model for the formation of the Earth and Moon from a single cloud of primitive (chondritic) composition. The model is based on the modified method of particle dynamics. We introduced the following additional interactions between particles: long-range gravitational attraction, short-range viscoelastic interaction related to collisions, and gas dynamic repulsion due to the evaporation of matter from particle surface. It was shown that the gas dynamic repulsion reduces the interaction energy and allows fragmentation of a cloud whose momentum corresponds to that of the Earth-Moon system. Computer modeling indicated that the accumulation of dispersed dust material provides a faster growth rate of the larger of the two bodies. This is why the Moon retained relatively low iron abundance, whereas the Earth accumulated most of the remaining dust cloud and acquired its high iron content. If the proposed model is valid, it is necessary to revise current concepts on the formation of planet-satellite systems.

HISTORY OF THE PROBLEM OF MOON FORMATION

The investigation of the origin of the Moon has a rather long history. At the end of the 19th century, Sir George Darwin [1] advanced the hypothesis that the Moon had separated from the Earth. Various modifications of this hypothesis had been developed by Ringwood [2], Cameron [3], O'Keefe [4], and other authors almost to the 1960s. However, this hypothesis was eventually rejected because the attainment of the necessary rotational instability requires an unrealistically high rotational momentum of the initial body, much higher than that of the Earth-Moon system. Another hypothesis implied capture of the Moon by the gravitational field of the Earth, but it was rejected as dynamically improbable. The third hypothesis was based on coaccretion. It was proposed by Ruskol [5] and developed by Harris and Kaula [6], who suggested that the Earth and Moon were formed from a common reservoir of solid planetesimals. They collided and crushed in the vicinity of the Earth. During this process, light silicate fragments were mainly retained on the orbit and iron-bearing fragments fell on Earth. This is the reason why the density of the Moon is lower than that of the Earth. However, the analysis of this hypothesis showed that

the proposed process of density fractionation is not efficient enough to account for the observed difference between iron abundances of the Moon and Earth [7]. The same is true of the variant of the coaccretion hypothesis discussed by Weidenschilling *et al.* [e.g., 8]. Subsequently, when more detailed information was obtained on the chemical composition of the Moon, it has become evident that the coaccretion hypothesis cannot also provide a plausible explanation for the depletion of volatiles and the enrichment of refractory elements in the Moon.

In the middle 1970s, two groups of American researchers [9,10] proposed a hypothesis of the impact origin of the Moon. This hypothesis suggests an impact of a planetary-size body (with the mass of Mars or larger) onto the Earth during the final stage of its accumulation. This collision ejected the molten material of the Earth's mantle into a low orbit, where it rapidly accumulated as the Earth's satellite Moon.

Computer calculations demonstrated the possibility of such a collision scenario [11, 12]. By that time, Wetherill [13] developed the hypothesis of Safronov [14] and showed that during the final stage of planetary body accumulation hundreds of bodies with masses larger than those of the Moon and Mars could occur in

the near-solar environment, and collisions between large bodies cannot be regarded as unique events. The catastrophic collision explained the high angular momentum of the Earth and the inclination of the Earth's axis to the ecliptic. The deficit of iron in the Moon could also be readily explained, because the hypothesis postulated that the collision had occurred after the formation of the Earth's core. Iron was concentrated in the core and the Moon was formed mainly from the material of the Earth's mantle.

CRITICISM OF THE GIANT IMPACT HYPOTHESIS AND A PROPOSED ALTERNATIVE

Until the 1970s, the problem of the origin of the Moon was mainly addressed by astronomers and researchers in the field of celestial mechanics. There was almost no evidence relative to the composition of the Moon. It was only known that the average density of the Moon (3.3 g/cm^3) is lower than that of the Earth (standard atmospheric pressure density of 4.45 g/cm^3). This difference is obviously due to the deficit of iron in the Moon. The Earth possesses an iron-nickel core accounting for 32% of the Earth mass (core contains about 10% light elements, O, S, and, probably, some other elements). Taking into account constraints imposed by the moment of inertia and density of the Moon, the lunar core cannot be larger than 5% of its total mass.

The analysis of samples returned by lunar missions showed that the chemistry of the Moon bears some resemblance to the composition of the Earth's mantle [15-17]. Extensive geological and geophysical data have been obtained for the Moon. Although these data were far from complete and remain open to discussion, they provided a basis for a more comprehensive analysis of the problem of the origin of lunar materials.

The oxygen isotopic compositions ($^{16}\text{O}/^{17}\text{O}/^{18}\text{O}$) of the Moon and the Earth appeared to be identical. In the $^{17}\text{O}/^{16}\text{O}$ versus $^{18}\text{O}/^{16}\text{O}$ diagram, samples from the Earth and Moon lie on a common fractionation trend, whereas other cosmic bodies, including meteorites of various classes, form separate fractionation lines [18]. The same characteristic cosmic zoning was established for the chromium isotope ratio; in this case, the $^{53}\text{Cr}/^{52}\text{Cr}$ ratios of the Moon and the Earth are identical and different from those of other cosmic objects [19]. This is strong evidence in favor of the kinship between lunar and terrestrial materials.

The problem of refractory element concentrations appeared to be controversial. The interpretation of geochemical and geophysical data suggested that the Moon is strongly enriched in refractory elements [20, 21]. However, this was in disagreement with the giant impact hypothesis. It was therefore necessary to accept that either the Moon had no relation to the Earth's mantle or it has lost much of its Si and Mg, which cannot be explained within the giant impact con-

cept. Because of this, the proponents of the giant impact hypothesis claimed that the terrestrial and lunar abundances of refractory elements, including rock-forming Al, Ca, and Ti, were practically identical [16, 17].

The abundances of siderophile elements in the Moon are lower than in the Earth. This fact has been regarded as compelling evidence for the generation of the Moon from the Earth's mantle. Indeed, the Earth possesses a huge metallic core. Therefore, the migration of siderophile elements into the core and the corresponding depletion of the mantle are understandable. The Moon's core is relatively small, and the even stronger depletion of the Moon in siderophile element seems only possible if the initial material of the Moon was derived from the Earth's mantle, which had already lost part of its siderophile elements. The formation of the small lunar core provided additional depletion. However, the observed distribution of siderophile elements in the Moon could also have been obtained if the Moon had been formed from primordial material but its core was generated under conditions of incomplete (partial) melting [22, 23]. Moreover, in such a case, an even better consistency would be achieved between the observed and calculated abundances of siderophile elements compared with the model Moon formation from the Earth's mantle [23]. However, the mechanism of iron segregation into the core under conditions of low-degree melting (estimated as $\sim 13\%$ [23]) would still be questionable.

It was previously thought that the giant impact hypothesis provided a simple explanation for the loss of volatile components from the Moon, including the alkali elements K, Na, and Rb, which are significantly depleted in the Moon as compared with the Earth. Indeed, the volatile components of melt could have been evaporated during the ejection of molten material into near-Earth space. However, this suggestion appeared to be related to another difficulty. Evaporation into free space must be accompanied by isotopic fractionation, and the residual melt must be enriched in heavy isotopes. However, the analysis of the isotopic composition of the lunar material did not reveal its measurable differences from the isotopic composition of terrestrial materials. There is a contradiction between the depletion of volatile components on the Moon relative to the Earth and the absence of isotope fractionation effects.

In recent years, a more sophisticated analysis has revealed difficulties in the dynamic aspect of the giant impact model. In particular, it appeared necessary to assume that the relative mass of the body (impactor) colliding with the Earth was higher than the previously estimate (3 : 7 rather than 1 : 10 [24]). But in such a case, the contribution of the impactor material to the Moon would have been higher than that of the Earth's mantle. Therefore, the attractive arguments of the initial giant impact concept based on the chemical resemblance of the lunar materials and the Earth's mantle

have lost much of their significance. Moreover, the observed identity of the isotopic compositions of oxygen ($^{18}\text{O}/^{17}\text{O}/^{16}\text{O}$) and chromium ($^{53}\text{Cr}/^{52}\text{Cr}$) in the Earth and Moon must be considered a fortuitous coincidence. In fact, in such a case, the similarity of geochemical parameters becomes an argument against the giant impact hypothesis.

Could the Moon have been formed under some conditions from the primitive (chondritic) matter rather than from the differentiated material of the Earth's mantle; i.e., is there a geochemical alternative to the giant impact hypothesis? Galimov [25, 26] demonstrated that the Moon could have been generated from the primitive material, if the Moon and the Earth were formed as a double system through the collapse of a cloud of hot dust particles of primitive composition.

The problem of origin of lunar materials was considered in our previous publication [23]. It was shown that the deficit of iron in the Moon can be explained by its relatively high volatility and evaporative loss. The process of evaporation explains both the loss of volatiles and iron and the partial loss of Si and Mg. This in turn explains the phenomenon of the enrichment of refractory oxides (Al_2O_3 , CaO , and TiO_2) in the Moon, because the abundances of these major oxides could only be increased at the expense of the corresponding removal of other major oxides, SiO_2 , MgO , and FeO [23, 25]. Thus, the observed composition of the Moon is consistent with its formation from the primitive material (similar to carbonaceous chondrites) rather than from the mantle materials of the differentiated planet, which is supposed by the giant impact hypothesis. The process of evaporation plays a key role. However, in order to prevent isotope fractionation, the evaporation must occur reversibly in a practically closed system, i.e., under conditions approaching equilibrium between a condensed phase and saturated vapor. In such a case, isotope fractionation is controlled by the thermodynamic isotopic effect, which is negligible at high temperature for such elements as K, Si, Mg, and others in liquid/solid-vapor systems. The conditions of closed-system evaporation are practically met during the collapse of a cloud of evaporating dust particles [23].

The goal of this study was to examine the dynamic behavior of such a cloud and to answer the question if a system of two bodies with dynamic characteristics of the Earth-Moon system (total angular momentum, mass, etc.) could be formed by its collapse.

As will be shown in the following analysis, the factor of evaporation plays also a key role in the dynamic model.

SOME ASPECTS OF THE ACCUMULATION OF PLANETS USED AS A BASIS FOR THE MODEL

Let us begin with the statement that our model is based on a nontraditional concept of the accumulation

mechanism of planets. The currently accepted model of accumulation was substantiated by Safronov and his colleagues [14, 27] and developed by Wetherill [13, 28], who considered the growth of planets the result of collision of solid bodies, planetesimals. It is assumed that meter-sized bodies are initially formed followed by bodies of kilometer and thousand-kilometer scales. The size of planetesimals increases owing to mutual collisions. The formation of the Moon is regarded in this concept as a result of collision of large planetary-size bodies during the final stage of accumulation.

We assumed that there was no initial formation of solid bodies. In the gas-dust solar nebula, dust precipitation on the central disk was accompanied by the occurrence of gravitational instability, which caused the formation of separate dust clumps. These aggregates collided and grew in size. The ideas of formation of planet-satellite systems by the accumulation of such clumps were proposed by Qurevich and Lebedinskii [29] and Eneev and Kozlov [30]. Although the agglutination of individual particles and their limited growth might occur, several factors prevented consolidation and kept the particles in a dispersed state. Among such factors were high radiation due to decay of short-lived isotopes, especially intense during the first 10^3 - 10^4 y of solar system history, electrostatic repulsion caused by the ionization of particles, and evaporation of volatile components (water and gases) from the surface of particles.

At a certain stage of accumulation, the mass of a dust clump may become sufficient for its gravitational collapse. Another important point in our model is the suggestion that the accumulation of clumps coincided with the T-Tauri phase; i.e., it occurred together with the development of intense solar corpuscular radiation (solar wind) blowing away gases (hydrogen and other volatile components) from the inner zone of the solar system [25].

The question as to the stage of the growth of the protoplanetary clump when its collapse and the consolidation of the solid body begins is not yet solved. It is evident that particular accretion history depends on a number of factors, including the initial composition of particles, proximity to the sun, pressure of enclosing gas, momentum, etc. As will be shown below, our model implies that the collapse of a cloud of particles was associated with the formation of the Moon and the Earth's embryo; we believe therefore that dust clumps could grow at least up to several lunar masses. However, in the numerical model presented below, we started from the less probable but better defined suggestion that the dust cloud had a mass corresponded to the total mass of the modern Earth and Moon and its momentum was equal to the momentum of the Earth-Moon system. This allowed us to avoid any arbitrary assumption and imposed tight quantitative constraints on the model.

DYNAMIC MODEL

The method of particle dynamics [31, 32] is used for the investigation of the collapse of a dust cloud. The method presents the matter as an ensemble of interacting particles described by the classic equation of Newtonian dynamics:

$$m\ddot{r}_k = \sum_{n=1}^N \frac{1}{r_{kn}} f(r_{kn}, \dot{r}_{kn}) \mathbf{r}_{kn}, \quad (1)$$

$$\mathbf{r}_{kn} = \mathbf{r}_k - \mathbf{r}_n, \quad r_{kn} = |\mathbf{r}_{kn}|; \quad k = 1, 2, \dots, N,$$

where r_k is the radius vector of the k th particle, m is the mass of the particle, N is the total number of particles, and $f(r, \dot{r})$ is the force of interaction between particles, which will be specified by the equation

$$f(r, \dot{r}) = \frac{A_1}{r^2} + \frac{A_2}{r^p} + \frac{A_3}{r^q} \dot{r}. \quad (2)$$

The first term in Eq. (2) represents the force of gravitational interaction, and, correspondingly, the coefficient A_1 is defined as $A_1 = -\gamma m^2$, where γ is the gravitational constant. The second term accounts for the repulsive force due to particle collision. The exponent p is taken to be 13, which provides adequate agreement with experimental data on the shock compression of solids [33, 34]. Let us assume that the equilibrium distance between two particles (equal to the particle diameter), a , is established by the balance of attraction and repulsion, i.e., $f(a, 0) = 0$, then we obtain from Eq. (2) $A_2 = -A_1 a^{p-2}$.

The third term describes dissipation, i.e., energy losses due to particle collision. Assuming that the second and third terms must vary proportionally to each other when the distance between particles changes, we obtain $q = p + 1 = 14$. Taking into account the aforementioned assumptions, Eq. (2) can be recast as follows:

$$f(r, \dot{r}) = \gamma \frac{m^2}{a^2} \left[\left(\frac{a}{r} \right)^{13} \left(1 - \beta \frac{\dot{r}}{r} \right) - \left(\frac{a}{r} \right)^2 \right], \quad (3)$$

where $\beta = -A_3/A_2 > 0$ is the dissipation factor.

The problem becomes fully specified by setting initial conditions: the position and velocity vectors of all particles. The initial shape of the dust cloud is a two-dimensional circular disk with a particle density distribution described by the equation

$$\xi(r) = \xi(0) \sqrt{1 - (r/R_0)^2}, \quad (4)$$

where $\xi(r)$ is the running density, r is the distance from

the center, R_0 is the radius of the disk, $\xi_0 = \frac{3}{2} \bar{\xi}$, and $\bar{\xi}$

is the mean density of the cloud. The distribution given by Eq. (4) allows solid body rotation [35] with the angular velocity

$$\omega_s = \sqrt{\frac{\pi^2 \gamma \xi(0)}{2R_0}}. \quad (5)$$

Solid body rotation of the cloud with the angular velocity $\omega_0 \leq \omega_s$ is imposed at the initial time. In addition, a random velocity vector modeling chaotic components of particle movement may be added to the particle velocities.

Let us assume that the energy lost owing to the action of the dissipative component of the interaction force is transformed into the internal energy of particles according to the equation

$$U_k = \sum_{n=1}^N Q(r_{kn}, \dot{r}_{kn}) - \lambda U_k, \quad (6)$$

$$Q(r, \dot{r}) = -\frac{A_3}{r^{p+1}} \dot{r}^2, \quad k = 1, 2, \dots, N,$$

where U_k is the internal energy of the k th particle; $Q(r, \dot{r})$ is the amount of heat transformed into internal energy as a result of the action of dissipative forces; A_3 is the coefficient allowing for the losses of thermal energy owing to its transfer from the particle to the ambient gas, radiation, and gas evaporation from the surface of the particle; and $A_3 = \beta \gamma m^2 a^{p-2}$ in agreement with Eqs. (2) and (3). In addition, heat exchange between particles was taken into account. To a first approximation, the temperature of a particle is expected to be proportional to its internal energy calculated using Eq. (6). Note that the inverse thermal effects on the dynamics of the system are ignored in this study.

Dimensionless similarity variables of the computer model and the system modeled are needed for numerical modeling. The main similarity parameter is taken to be

$$\alpha = \frac{K^2}{\gamma M^3 R_c}, \quad (7)$$

where K is the momentum; R_c is the radius of the sphere comprising the total mass (M) of all particles in the system, $R_c = (3M/4\rho_c)^{1/3}$; and ρ_c is the mean density of the material. The values of the aforementioned dimensional quantities and the calculated parameter a for the Earth-Moon system are

$$K = 3.45 \times 10^{34} \text{ kg m}^2/\text{s}, \quad M = 6.05 \times 10^{24} \text{ kg.}$$

$$R_c = 6.41 \times 10^6 \text{ m}; \quad \gamma = 6.67 \times 10^{-11} \text{ m}^3/(\text{kg s}^2).$$

$$\alpha = 0.0126.$$

It can be shown that the dimensionless dynamic parameter α defined by Eq. (7) is proportional to the ratio of the kinetic energy of system rotation to the potential energy of the gravitational interaction of the matter within the system. On the other hand, the similarity coefficient α is proportional to the square of the

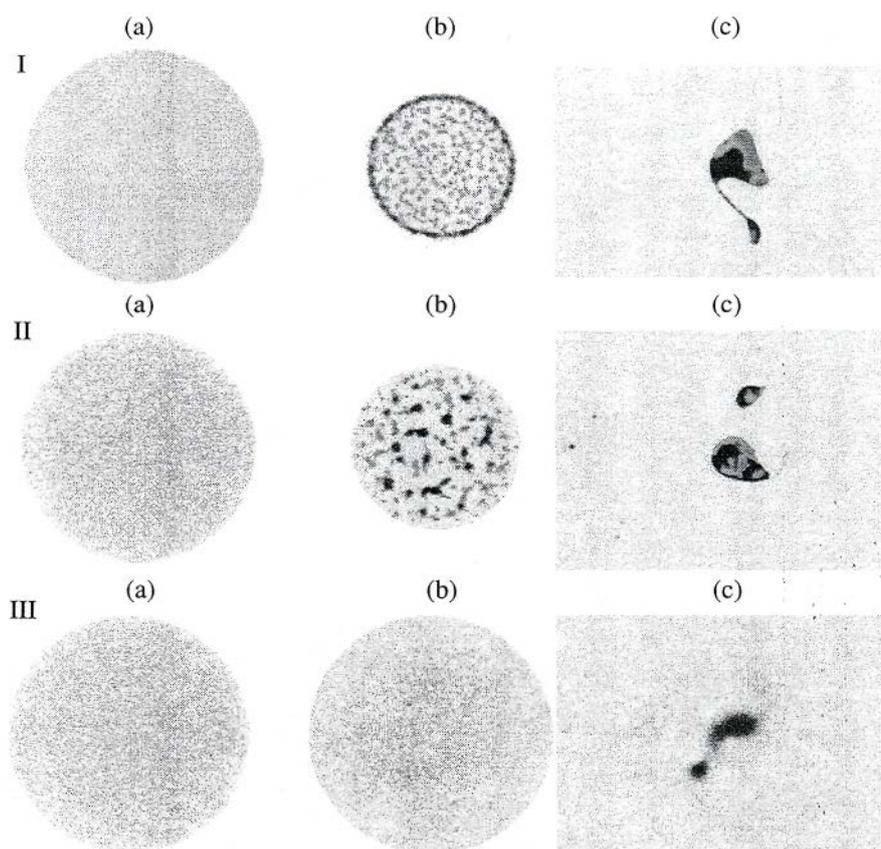


Fig. 1. Computer simulation of the collapse of a cloud of particles: (I) uniform initial distribution of particles within the cloud, (II) nonuniform distribution (see text), and (III) nonuniform distribution accounting for chaotic motion of particles. Frames (a), (b), and (c) correspond to sequential time moments illustrating the initial state, compression, and fragmentation of the cloud, respectively; cOQ/Oj value is arbitrary, satisfactory for the manifestation of fragmentation.

initial angular velocity of the cloud, ω_0 (used in the initial conditions for modeling):

$$\alpha = \frac{3\pi}{4} \left(\frac{R_i}{R_0} \right)^4 \frac{R_0}{R_c} \left(\frac{\omega_0}{\omega_s} \right)^2, \quad (8)$$

where R_i is the radius of inertia of the cloud. Equation (8) allows us to establish the correspondence between the real and model systems.

In terms of mathematics, the problem is reduced to the solution of a Cauchy problem for a system of ordinary differential equations (1). However, during the direct solution of Eq. (1), the number of necessary operations at each step of integration appears to be proportional to N^2 , which hampers the computation of complex systems. Gravitational interactions are long-range, which prevents application of the cut-off radius that is used for the solutions of similar equations in molecular physics. Equation (1) is solved by the Barnes-Hut algorithm [36], including the hierarchical partition of the calculated domain into squares with sizes increasing in geometric progression with increasing distance from the particle considered. The use of this algorithm provided the number of operations to be proportional to $N \log N$, which greatly increased the size of systems that could be calculated. The computer implementation of

the Barnes-Hut algorithm was performed for these calculations by I.E. Volkovets.

Preliminary calculations showed that the character of collapse depends on the type of initial density distribution within the cloud. Figure 1 (I) illustrates the evolution of a cloud with uniform initial density distribution. A hot compressing ring is formed along the margin of the cloud, whereas the matter within the ring is essentially in an equilibrium state. This case is however physically unrealistic. Figure 1 (II) presents the evolution of a similar cloud with the same number of particles and the same initial momentum but with a density distribution specified by the following law: $\xi(r) =$

$\xi_0 \sqrt{1 - (r/R_0)^2}$. In such a case, the cloud contracts uniformly. Clusters clearly visible in Fig. 1 (II) appear as a result of the Jeans instability [33] of matter within the cloud. The third case (Fig. 1 (III)) differs from the previous one in the presence of a random component in particle velocities. The chaotic movement of particles strongly suppresses the Jeans instability, and this case was used as a basis for our computer model.

Equation (8) implies that the momentum of the real Earth-Moon system corresponds to the value $\omega_0/\omega_s = 0.08$. Figure 2 shows the results of calculation of the

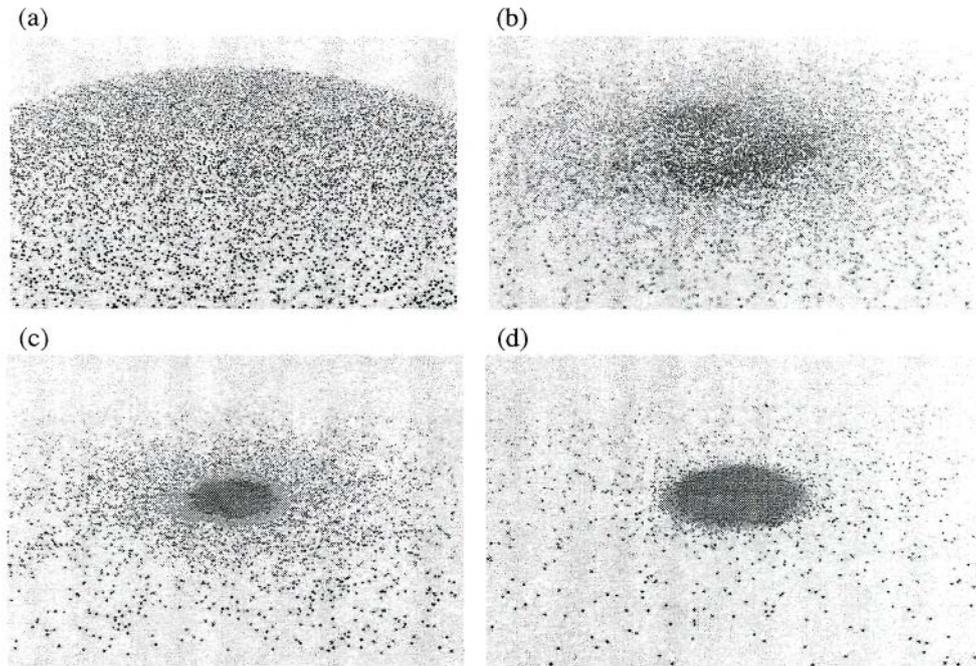


Fig. 2. Computer simulation of the rotational collapse of a cloud of particles (oblique projection) corresponding to the Earth-Moon system parameters. $R_0 = 5.51R_C$, $N = 10^4$, and $\omega_0/\omega_s = 0.08$ (without considering the evaporation factor) in the system, (a) $t = 0$, (b) $t = 0.16T_s$ (c) $t = 0.2T_s$ and (d) $t = 0.32T_s$.

rotational collapse of a dust cloud in oblique projection for the particle number $N = 10^4$ and the initial cloud radius $R_0 = 5.51R_C$. The number of particles is controlled by the computation procedure. This does not mean that the mass of each particle is the mass of the cloud divided by 10^4 . Physically, we considered the masses of millimeter-sized particles. The random component of particle velocities in the initial configuration is taken from the uniform distribution with the maximum value of $0.68 \omega_s R_0$. The time corresponding to the sequential frames in Fig. 2 is measured in units of $T_s = 2\pi/\omega_s$, which is the period of solid-body rotation in the initial configuration. The tints of grey color on this figure show the temperature distribution in the system (the most dark correspond to the highest temperature). It can be seen that the collapse is accompanied by the formation of a hot condensed body. However, there is no fragmentation of the cloud and, in particular, no formation of a binary system of the Earth-Moon type.

Figure 3 presents the analysis of the dependence of rotational instability on ω_0/ω_s . It can be seen that collapse-related fragmentation does not occur if the relative angular velocity ω_0/ω_s is lower than a critical value of about 0.42 (Fig. 3a). If the ω_0/ω_s ratio is higher than the critical value, two bodies of different sizes are formed (Figs. 3b, 3c). When $\omega_0/\omega_s = 0.76$, the sizes of the bodies converge (Fig. 3d), and a further increase in ω_0/ω_s results in the formation of three or more fragments (Figs. 3e, 3f). The momentum of the Earth-

Moon system ($\omega_0/\omega_s = 0.08$) is much lower than the critical value (0.42) necessary for the formation of rotational instability.

This result is not surprising. There have been many attempts to explain the formation of the Moon by its derivation from the Earth, but all of them could not overcome the problem of insufficient momentum for the separation of the Earth and Moon. Thus, it appears as if we have obtained additional evidence for the impossibility of Moon formation as a result of rotational instability in the initial system.

But the situation changes dramatically if the evaporation process is taken into account [23]. As was noted above, the depletion of volatiles in the Moon coupled with the absence of isotopic fractionation is consistent with the evaporation of dust particles into the volume of the dust cloud. The evaporation process generates an additional force which must be accounted for in kinetic equations (1). Under the equilibrium pressure of vapor saturation, an increase in mass flux related to evaporation from the surface of a particle generates a repulsive force, which can be approximately described by the equation

$$f_v = \frac{\pi v \nu a^4}{16r^2}, \quad (9)$$

where v is the additional mass of matter evaporated from the unit surface area of the particle per time unit and ν is the average velocity of molecules escaping

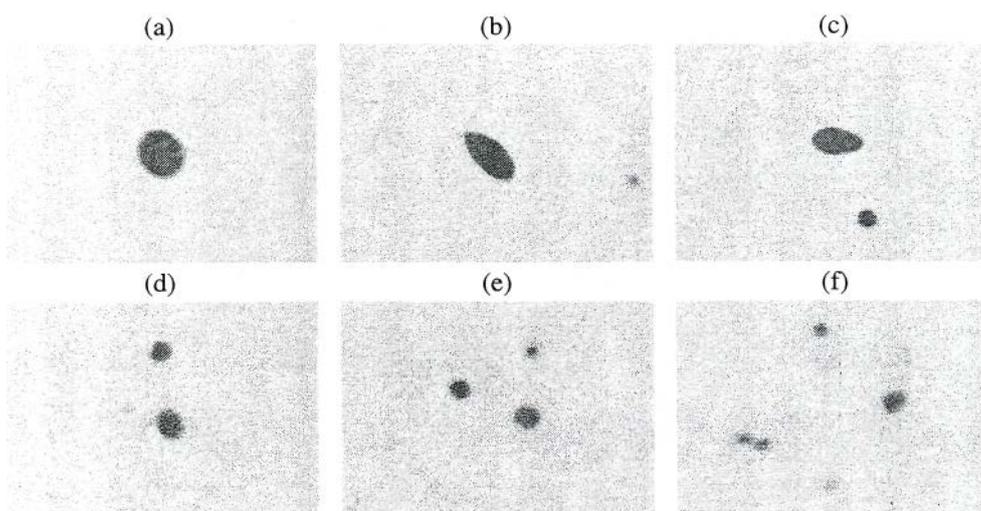


Fig. 3. The results of calculation of rotational collapse for different values of the initial angular velocity, ω_0/ω_s : (a) 0.29, (b) 0.42, (c) 0.54, (d) 0.76, (e) 0.80, and (f) 0.85.

from the particle surface. According to Eq. (9), the force of gas dynamic repulsion is proportional to the square of distance between the particles. Consequently, it can be combined with the gravitational force:

$$f = f_\gamma - f_v \approx \left(\gamma - \frac{9\nu\nu}{4\pi a^2 \rho^2} \right) \frac{m^2}{r^2} \approx \gamma' \frac{m^2}{r^2}. \quad (10)$$

This formula implies that the forces of gas dynamic repulsion and gravitational attraction may cancel each other ($\gamma' = 0$), if the particles are sufficiently small.

As was shown above, the occurrence of rotational instability is controlled by the dimensionless dynamic parameter α , which involves γ or its effective value γ' . This allows us to determine the intensity of evaporation sufficient for the appearance of rotational instability at an angular momentum value corresponding to the real Earth-Moon system. The rotational instability that causes the formation of two separate bodies occurs at a dimensionless angular velocity between $\omega_0/\omega_s = 0.42$ and $\omega_0/\omega_s = 0.76$, which is higher by a factor of 5.3-9.5 than the $C0_0/Cf_s$ value calculated for the Earth-Moon system. Since α is proportional to the square of angular velocity, the γ' value must be lower than γ by a factor of at least 28.

Using Eq. (10) and the expression $\nu = \sqrt{8RT/\pi}$ [35], it can be readily shown that the ν value necessary for the appearance of rotational instability with $\omega_0/\omega_s = 0.70$ is

$$\nu \approx 0.87 \frac{\gamma \rho^2 a^2}{\sqrt{RT}}. \quad (11)$$

Figure 4 shows the results of computer modeling with the same parameters as in Fig. 2, but allowing for evaporation-related repulsive forces. In contrast to the

patterns shown in Fig. 3, it can be seen that the collapse is accompanied by the formation of two clumps, which gradually transform into condensed bodies.

Note that the main factor is not the intensity of evaporation but its increase under conditions of dynamic equilibrium between the condensed matter and vapor. Under such an equilibrium (reversible) increase in the intensity of evaporation, isotopic fractionation is controlled by the thermodynamic isotopic effect.

For particles with sizes of meteoritic chondrules ($a \approx 1$ mm), a temperature of about 10^3 K, and a density between 10^3 and 2×10^3 kg/m³, the ν value is about 10^{-13} kg/(m² s) (for $R \approx 400$ J/(kg K)). Consequently, a very small increase in the intensity of evaporation can sustain the equilibrium state of a gas-dust cloud.

It can be shown that the time required to reduce the mass of a particle by Δm is

$$t = 0.59 \frac{\sqrt{RT}}{\gamma \rho a} \left[\left(1 - \frac{\Delta m}{m} \right)^{-1/3} - 1 \right]. \quad (12)$$

For instance, a 40% decrease of particle mass under the aforementioned conditions requires between 3×10^4 and 7×10^4 y. The period 10^4 - 10^5 y can be considered as the characteristic time of formation of two bodies from a dust cloud with the parameters of the Earth-Moon system.

We deliberately considered the example of the evaporation of 40% of the particle mass. It was previously shown [23] that the evaporation of about 40 wt % of chondritic melt produces a residue composition corresponding to the composition of the Moon, including the abundances of iron and refractory elements.

Thus, we obtained a model internally consistent in physicochemical and dynamic aspects. The key process providing such a consistency is evaporation.

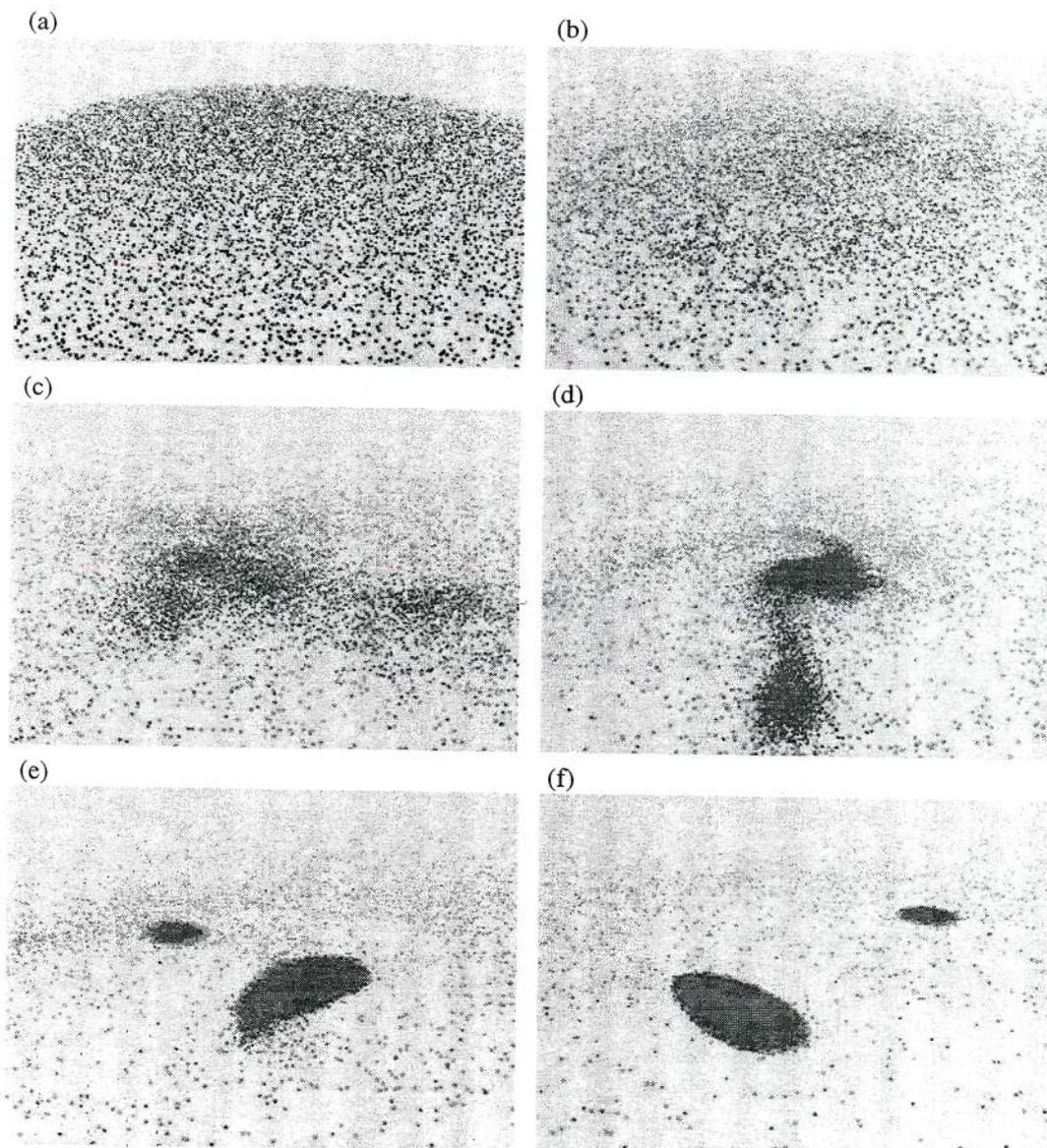


Fig. 4. Computer simulation of the rotational collapse of a cloud of evaporating particles. The conditions are the same as in Fig. 2. except $\omega_0/\omega_s = 0.70$. The successive frames correspond to the following moments of time: $t =$ (a) 0, (b) $0.21T_s$ (c) $0.41T_s$ (d) $0.58T_s$ (e) $0.80T_s$ (f) $1.07T_s$.

ASYMMETRIC ACCRETION OF UNEQUAL FRAGMENTS

Both the forming fragments, one of which should transform into the Moon and the other into the Earth, must be initially depleted in iron (as a result of evaporation) to the same extent. The question arises as to why the Moon retained its iron deficit, whereas the Earth shows no iron depletion compared with the initial composition. In fact, the Earth is even richer in iron than carbonaceous chondrites, which are regarded as a proxy for the primordial matter. This phenomenon is beyond the scope of this paper. We address here the deficit of iron in the Moon and the lack of such a deficit in the Earth. Our explanation is based on some character-

istic features of the subsequent evolution of the particle cloud after its fragmentation to consolidated bodies.

An important feature of the collapse accompanying chaotic particle movement is that, after the formation of condensed bodies, a considerable portion of particles remains dispersed in the space of Fig. 5, and the temperature of such dispersed particles is much lower than the temperature of the condensed bodies.

This material gradually precipitates on the formed embryos. It is obvious that if a cloud moving on a circular orbit around the sun were considered instead of the isolated cloud, the dust trail would be even more extended in space and the process would be prolonged.

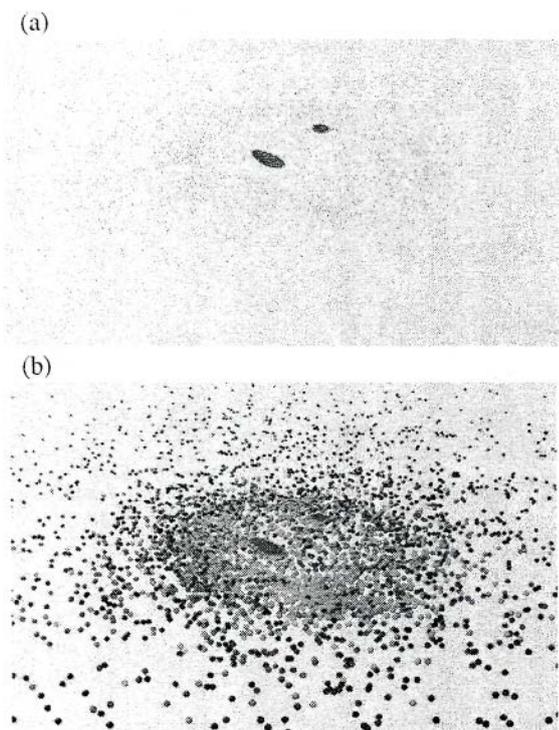


Fig. 5. Cloud of particles surrounding forming bodies ($t = 1.07T_3$): (a) normal view and (b) the radii of particles are enlarged to better visualize the cloud.

The growth of planetary embryos by the accumulation of cold cloud matter can be modeled ignoring interaction between particles and considering only the dynamics of their movement in the gravitational field of two massive bodies. A question arises as to how these bodies will increase their masses accumulating particles from the environment. In order to answer this question, we conducted a computer experiment.

A particle with a mass of m was placed into a system of two bodies with masses of M_1 and M_2 (rotating about the common center of gravity). The initial position of the particle is selected randomly on the circle C_R with radius R and the center coinciding with the center of gravity of the two-body system (Fig. 6a). The movement of the particle was calculated in the gravitational field of the two bodies. This modeling included the calculation of the number of particles falling on the first (n_1) and second (n_2) bodies and escaping from the system (n_3).

Computer modeling [38] showed that a more massive body accumulated more particles (Fig. 6b). The dependency between the mass ratio of the bodies and the ratio of the number of particles accumulated by them can be approximated by a quadratic function. Thus, an accidental initial difference between the masses of bodies must lead to the situation when the mass of the smaller body changes relatively slowly, whereas the larger body accumulates most particles dispersed in the environment.

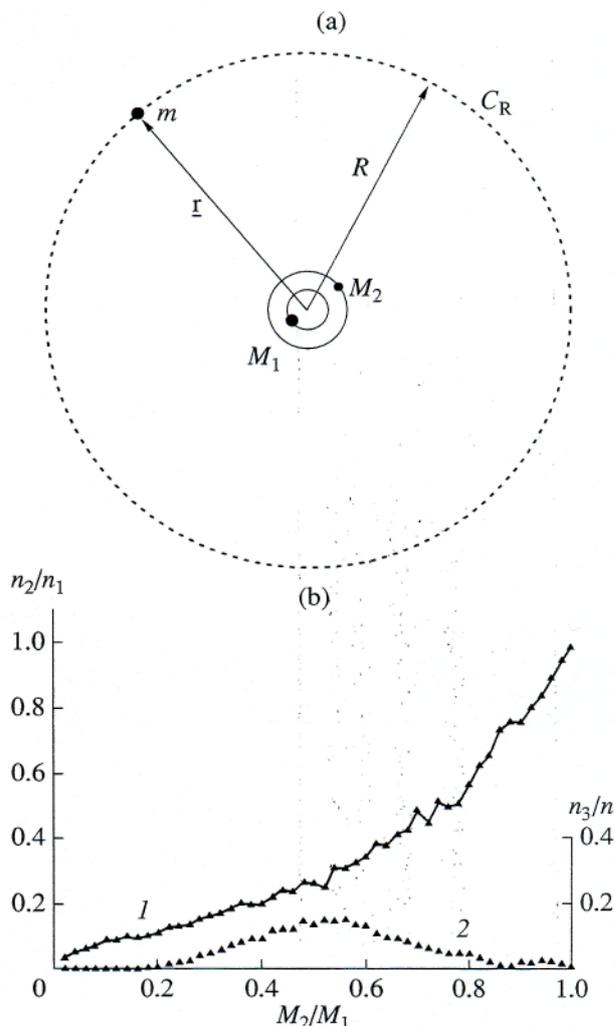


Fig. 6. Simulation of the growth of a planetary embryo, (a) The model of two bodies, M_1 and M_2 , revolving about their common center of masses and a particle m starting from the distance R and moving in the gravitational field of M_1 and M_2 . (b) Results of computer simulation: curve 1 shows the relative number of particles (n_1/n_2) accumulated by the bodies depending on the ratio of their masses, M_2/M_1 , and curve 2 shows the relative number of particles, n_3/n , expelled beyond the circle R for the total number of particles $n = 5000$.

In other words, the high-temperature embryos of the Earth and Moon were initially similarly depleted in iron. The smaller fragment (future Moon) has retained its relatively low iron content, while the larger fragment (future Earth) has accumulated almost all the dispersed matter of the gas-dust cloud, which provided a relatively high iron content of the cloud.

CONCLUDING REMARKS

Thus, the depletion of volatiles coupled with the lack of isotopic fractionation and the deficit of iron in the Moon's composition can be explained by the model

proposed here. In this paper, we did not consider other geochemical parameters. The problems of siderophile element distribution in lunar materials and the interpretation of the Hf-W systematics in the light of the proposed concept were discussed in [23]. As to the refractory elements, it should be noted that our model is consistent with the estimates implying higher concentrations of refractory elements in the Moon compared with the Earth (e.g., [15]).

Our model leaves open the problem of the specific stage of protoplanetary cloud development when it separated into the embryonic Earth and Moon. In order to avoid arbitrary empirical estimates, we used the real parameters of the Earth-Moon system. That is, we assumed that the collapse had developed in a cloud the mass of which was equal to the mass of the Earth-Moon system. However, it is likely that the process of mass separation could occur in a cloud with a smaller mass and could be followed by the further growth of the Earth and Moon embryos at the expense of dispersed material orbiting the sun. It is also possible that the accumulation of planets or, more specifically, planet-satellite systems occurred in two stages. The first stage produced gas and dust clumps. Radiation prevented their preliminary consolidation. After a time period of about 10^6 y, the primary clumps began collapsing, and the largest of them became planetary embryos. During the final stage, the planetary bodies could grow at the expense of collision with solid bodies of presumably asteroid sizes.

One of the requirements of our model is that large dust clumps rather than an ensemble of solid bodies were formed and grew during the early stage of development of the protoplanetary disk. If this is the case, our model not only has a bearing on the origin of the Earth-Moon system but also indicates the need to revise the theories of accumulation of planets from the new viewpoint. • ' :

There remain several problems concerning the following aspects of the hypothesis.

(1) It is necessary to calculate more comprehensively the temperature profile in the collapsing cloud and perform a thermodynamic analysis of element distribution in the particle-vapor system at various levels of this profile. Until this is done, the model remains a qualitative hypothesis.

(2) A more rigorous expression should be obtained for gas dynamic repulsion accounting for the local action of this force in contrast to gravitational interaction.

(3) The model ignored the problem of the influence of the sun. The radius of the disk was taken arbitrarily. The deforming effect of clump collisions during disk formation was not considered.

(4) A more reliable solution can be obtained by using a three-dimensional formulation of the problem and increasing the number of particles, N .

(5) It is necessary to examine the cases of formation of a binary system from a protodisk that is lighter than the total mass of the Earth-Moon system, because it is highly probable that the process of accumulation included two stages: an early stage of the collapse of the dust clump and the late stage when an additional growth was related to the collision of solid bodies formed by that time in the solar system.

(6) The significant inclination of the Earth's axis to the ecliptic is not explained by the dynamic part of our model of the Earth-Moon system, whereas the hypothesis of giant impact provides such an explanation.

Answers to these questions rely to a large extent on the general solution of the aforementioned problem of the evolution of clumps in the protoplanetary circum-solar gas-dust disk.

Finally, it should be kept in mind that our hypothesis invokes some elements of heterogeneous accretion, although in the sense opposite to the universally accepted one. Proponents of heterogeneous accretion conjectured that an iron core was initially formed in planets by one way or another, after which a silicate mantle overgrew the core. In our model, the initial embryo is depleted in iron, and an iron-rich material is supplied only during the subsequent accumulation. It is clear that this strongly affects the process of core formation and the related conditions of siderophile element fractionation, Hf-W systematics, and other geochemical characteristics. Thus, the proposed concept opens new avenues for research in both the dynamics of formation of the solar system and geochemistry.

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