Origin of the Earth–Moon system

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At present, hypothesis of the formation of the Moon from material of the Earth-mantle is a paradigm. It suggests collision of the Earth with a large (Mars-size) body during the first 30–50 million years of the Earth history. This hypothesis, known as the Giant Impact Hypothesis (GIH), was coined in the middle of the 1970s and gained acceptance because it provided a simple solution for a number of dynamic and geochemical problems (Hartmann and Davis 1975; Cameron and Ward 1976). Primarily, it explains iron deficiency in the Moon as the Moon is proposed to have originated from the Earth's mantle after the planetary iron had already concentrated in the Earth's core.

However, during the course of time some inconsistencies of the impact hypothesis have surfaced. It is not the purpose of this article to make a critical review of Giant Impact Hypothesis. Instead, we would like to show another mechanism of the formation of the Moon, different from the collision model (GIH), which considers the geochemical constraints.

First of all, it should be stressed that there exists a significant geochemical similarity of the lunar and Earth's mantle material, including their oxygen and chromium isotope ratios. Both the Earth and Moon samples follow the same ^{16}O-^{17}O-^{18}O isotope fractionation line, have the same $^{53}Cr/^{52}Cr$ isotope ratios (Lugmair and Shukolyukov 1998; Clayton and Mayeda 1975). The discovery of such a similarity invalidates any propositions which consider the Earth and Moon as alien bodies, for instance, the hypothesis of the capture of the Moon by the Earth.

At the same time, there are some important differences between the composition of the Earth and that of the Moon. The first major difference is depletion of iron content in the Moon. It is explained in the GIH by proposing that the Moon was formed from the Earth's mantle material, after most of the iron sank to the core. Indeed, while the Earth contains about 32.5% iron, the Moon has only about 10–15%. However, concentration of FeO in the Earth's mantle is about 8%, compared to 13% in the Moon. In GIH, it has been proposed that the additional iron might have come from the impactor. Recent versions of the impact model admit contribution from the impactor in the lunar material to be predominant. However in such a case, the protolunar material should have been enriched in associated siderophile elements, whereas, in fact, the Moon is depleted in siderophile elements. Moreover, the idea that the Moon mainly inherited the impactor's material of unknown composition devalues the geochemical arguments and is contrary to the main features of similarity between the Moon and the Earth, including their similarity in oxygen and chromium isotope composition, which in cosmochemistry, plays the same role as DNA plays in the identification of genetic relation of organisms.

The second important difference is the volatile content. Figure 1 illustrates the depletion of the Moon in some elements as a function of their volatility. This is the well known Ringwood curve and the same data are given in tables 1 and 2. The Earth is also depleted in volatiles relative to

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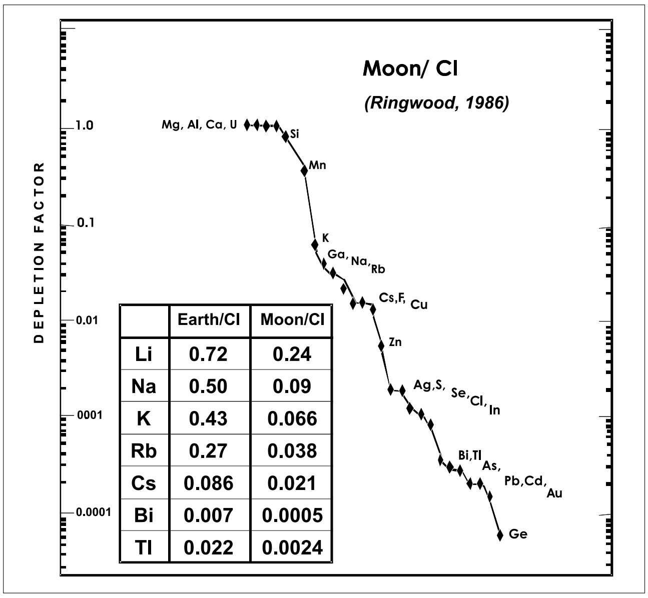

	Earth/CI	Moon/CI
Li	0.72	0.24
Na	0.50	0.09
K	0.43	0.066
Rb	0.27	0.038
Cs	0.086	0.021
Bi	0.007	0.0005
Tl	0.022	0.0024

Figure 1. Depletion of the Moon and Earth in volatiles (data from Ringwood 1986; Jones and Palme 2000).

Table 1. *Comparison of the composition of the Earth, Moon and CI chondrites (after Taylor 1986).*

Component	CI	Silicate Earth	Moon
SiO_2	34.2	49.9	43.4
TiO_2	0.11	0.16	0.3
Al_2O_3	2.44	3.64	6.0
FeO	35.8	8.0	13.0
MgO	23.7	35.1	32.0
CaO	1.89	2.89	4.5
Na_2O	0.98	0.34	0.09
K_2O	0.10	0.02	0.01

Table 2. *Relative abundance of elements normalized to Al in the Earth, Moon and chondritic material (CI).*

Element	CI	Earth	Moon (without core)
Si	12.3	12.0	6.4
Ti	0.05	0.05	0.05
Al	1.0	1.0	1.0
Fe	21.5	24.7	3.2
Mg	11.0	10.9	6.1
Ca	1.04	1.05	1.02
Na	0.57	0.13	0.02
K	0.06	0.01	0.0025

primitive carbonaceous chondrites but to a much lesser degree.

At first glance, depletion of the Moon in volatiles is quite consistent with its high temperature origin during catastrophic impact event (GIH). However such a process is expected to be accompanied by isotope fractionation whereas the loss of volatiles by the Moon has left no traces of isotope fractionation.

Table 3. *Isotopic fractionation observed in high temperature evaporation processes.*

Ratio	Process	Isotope fractionation
$^{26}Mg/^{24}Mg$	Under 40% loss of Mg	11–13‰
$^{30}Si/^{28}Si$	Under 40% loss of Si	8–10‰
$^{41}K/^{39}K$	Depletion of the Moon with coefficient 0.066	~ 60‰

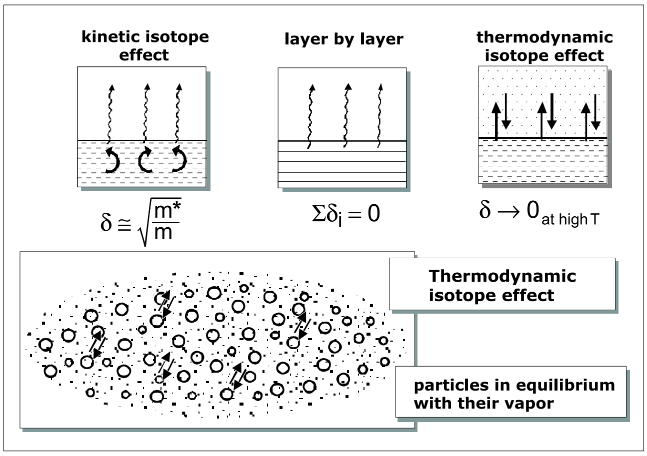

Figure 2. Mechanisms of isotope fractionation.

Experiments with high temperature evaporation of silicate melts under vacuum essentially showed isotopic fractionation of elements, including those in which the Moon is significantly depleted, for example, potassium (Wang *et al* 1994; Humayun and Clayton 1995). The results of these experiments are summarized in table 3.

It has been recently argued by Jones and Palme (2000) that evaporation is ruled out as a viable volatile depletion mechanism because of unavoidable isotope fractionation which has not been observed. However, it should be noted that the isotope fractionation may be absent or negligible in some other depletion processes.

Isotope fractionation during evaporation in vacuum is due to kinetic isotope effect (figure 2). One possible mechanism, when isotope fractionation during evaporation is absent, is layer-by-layer evaporation. This mechanism is implemented, for example, in the course of evaporation of a solid in vacuum (Davis *et al* 1990) or of a liquid, provided the rate of its internal mixing is lower than that of evaporation. However, layer-by-layer evaporation also rules out chemical fractionation, while the Moon shows different magnitude of loss of elements depending on their volatility without isotope fractionation.

The isotope fractionation is small if evaporation occurs reversibly (close to saturated vapor pressure). In such a case the extent of isotope fractionation is governed by the thermodynamic isotopic effect, which, unlike the kinetic isotopic effect, is negligible at high temperatures. However, this requires certain specific conditions, which have not been considered upto now. The evaporating particles must be surrounded by their vapor and be in equilibrium with it. Then the loss of chemical components from the particles will occur in accordance with their volatility and isotope fractionation will be controlled by negligible equilibrium (thermodynamic) isotopic effects. Such conditions are implemented in a cloud of dispersed particles. In a collapsing cloud, the heated particles evaporate while in equilibrium with their vapor and the vapor is gradually expelled into the outer zone of the cloud in the course of its contraction.

Few years ago, we suggested that the geochemical properties of the Moon and Earth might be explained by their formation as a double system from a common reservoir of particles (Galimov 1998). Presently, we have developed the relevant dynamic model and here we present results of its computer simulation. Let us for a while lay aside the generally acknowledged theory of planet accumulation by collision of solid planetesimals (the Safronov–Wetherill model), and consider the development of a cloud of particles assuming that planetary bodies are formed through collapse of such a particle cloud. We have used the particle dynamics method. The method consists of representing the matter as an assembly of interacting particles.

The motion of the particles is described by the equations of Newtonian dynamics:

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

where $\underline{r}$ is the radius-vector of the k-th particle and m is the particle mass.

The particle interaction force includes a number of terms:

$$f(r, \dot{r}) = -\frac{\gamma m m}{r^2} + \frac{A_2}{r^p} - \frac{\beta A_2 \dot{r}}{r^{p+1}}. \tag{2}$$

The first term on the right hand side is the gravitation interaction force, where γ is the gravitational constant. The second term is a repulsion force arising during the particle collision. This is a short-range force. The power coefficient p could be as high as 13. The third term takes into account the energy dissipation during particle collisions. This is a source of heating.

Initial conditions are defined by particle position and velocities. We take the initial shape of the cloud as a two-dimensional disk. At the initial moment the cloud rotates around the center as a rigid body. The linear density $\xi(r)$ of particle distribution is non-uniform. It changes in accordance with the following formula.

$$\xi(r) = \xi(0)\sqrt{1 - (r/R_0)^2}, \tag{3}$$

where r is the distance to the centre and R_0 is the disk radius.

Such a distribution allows a ‘solid-body rotation’. The angular velocity of this rotation ω_s is defined as

$$\omega_s = \sqrt{\frac{\pi^2 \gamma \xi(0)}{2R_0}} \tag{4}$$

where γ is the gravitational constant.

Besides, a random velocity vector, simulating the chaotic character of particle motion has been added to the velocities of the particles.

The numerical computation in a two-dimensional definition requires a transformation of parameters that in reality describe three-dimensional objects to a two-dimensional state. The similarity principle is satisfied by introducing a dimensionless parameter:

$$\alpha = \frac{K^2}{\gamma M^3 R_c}, \tag{5}$$

where K is the rotational momentum (moment of momentum) and R_c is the radius of a solid body concentrating the total mass (M) of all the particles in the system. For the case of the Earth–Moon system, the dimensional quantities and the corresponding dimensionless parameter α have the following values: $K = 3.45 \times 10^{34}\,\mathrm{kg} \cdot \mathrm{m}^2\,\mathrm{sec}^{-1}$; $M = 6.05 \times 10^{24}\,\mathrm{kg}$; $R_c = 6.41 \times 10^6\,\mathrm{m}$; $\gamma = 6.67 \times 10^{-11}\,\mathrm{kg}^{-1} \cdot \mathrm{m}^3 \cdot \mathrm{sec}^{-2}$; $\alpha = 0.0126$. On the other hand the coefficient α is proportional to $(\omega_0/\omega_s)^2$:

$$\alpha = \frac{3\pi}{4} \left(\frac{R_i}{R_0}\right)^4 \frac{R_0}{R_c} \left(\frac{\omega_0}{\omega_s}\right)^2 \tag{6}$$

where ω_0 is the initial angular velocity used in the computations ($0 < \omega_0 < \omega_s$).

Then we tried to compute the rotational collapse for a cloud of particles. The kinetic momentum of the actual Earth–Moon system corresponds to the value $\omega_0/\omega_s = 0.08$ (as can be inferred from equation (6). The number of particles is $N = 10^4$ and the initial radius of the cloud is $R_0 = 5.51\,R_c$.

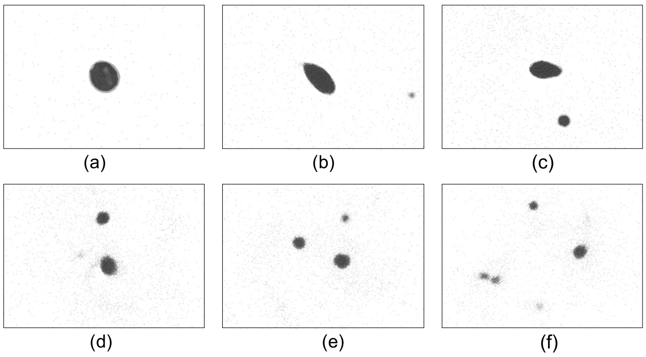

Figure 3. Results of computation of the rotational collapse for different values of the initial relative angular velocity ω_0/ω_s: **(a)** 0.29; **(b)** 0.42; **(c)** 0.54; **(d)** 0.76; **(e)** 0.80; **(f)** 0.85.

The collapse leads to the formation of a single body that is the angular momentum of the actual Earth–Moon system is insufficient to develop a rotational instability. This fact is in no way unexpected. Attempts have long since been made to explain the formation of the Moon by its separation from the Earth. It was, however, demonstrated that virtually no possible scenario of this process provides the angular momentum required for their separation. Indeed, the calculation shows that while the dimensionless parameter ω_0/ω_s is below 0.42, no fragmentation takes place in a rotational collapse (figure 3a). At higher values of the parameter, two different size bodies are formed (figure 3b, c); when $\omega_0/\omega_s = 0.75$, the sizes of the bodies become equal (figure 3d), and at still higher values of the parameter, multiple fragmentation occurs. Hence, we seem to have obtained yet another unsuccessful scenario of the Moon formation as a result of the rotational instability of the initial system. However, the situation changes drastically when one takes into account the evaporation process. As demonstrated above, the Moon's depletion in volatiles, and absence of isotope fractionation agrees with the process of particle evaporation into the space occupied by the particle cloud.

The flow evaporated from a particle surface produces a repulsive impulse with a force that can be approximately defined as:

$$f_V = \frac{\pi \nu v a^4}{16 r^2}, \tag{7}$$

where ν is the intensity of flow from evaporating particle, and v is the average velocity of molecule torn off from the particle surface. Thus the evaporation process generates an effect of one more force that should be accounted for in the equation of motion.

As both the gas-dynamical repulsion force and gravitational interaction force are inversely proportional to the squared inter-particle distance, they can be summed:

$$f = f_\gamma - f_\nu \simeq \left(\gamma - \frac{9\nu v}{4\pi a^2 \rho^2}\right)\frac{m^2}{r^2} \simeq \gamma' \frac{m^2}{r^2}. \tag{8}$$

The dimensionless dynamic parameter α includes the effective value γ'.

As mentioned above, the rotational instability appears when the value of the angular velocity ratio is between $\omega_0/\omega_s = 0.42$ and 0.80, while the value ω_0/ω_S calculated for the Earth–Moon system is 0.08. Since α, according to equation (6), depends on angular velocity squared, it means that the value of γ' is to be at least about $(0.42/0.08)^2$ times smaller that the value of γ.

Hence, from the expression

$$\left(\gamma - \frac{9\nu v}{4\pi a^2 \rho^2}\right) = \gamma' \tag{9}$$

we are able to calculate the evaporation intensity level sufficient to produce a rotationally unstable system that would have the parameters of the Earth–Moon system. For particles of the size of meteorite chondrules ($\sim 1\,\mathrm{mm}$), the temperature of the order of $10^3\,\mathrm{K}$, and density between 1.0 and $2.0\,\mathrm{g/cm^3}$, ν-value is of the order of $10^{-13}\,\mathrm{kg/m^2\,sec}$. Such an increase of the flow of evaporating material is equivalent to increase of the effective angular velocity (ω_0/ω_s) to a value exceeding 0.42. The calculation, taking into account the evaporation process by including the corresponding additional term in equation (7) into the dynamic equation (2), describes a collapse accompanied by formation of the two conglomerations of different sizes, which are being transformed into condensed bodies. These conglomerations have relatively elevated temperatures (figure 4).

An important feature of collapse with a chaotic component of particle velocity is that a significant fraction of particles stays scattered over the space after the condensed bodies are formed, and the temperature of these scattered particles is substantially lower than that of the condensed bodies. Later on, the scattered particles are accumulated by the condensed bodies, that take several orders of magnitude more time than the process of formation of condensed bodies (figure 5). Taking the intensity of evaporation as $10^{-13}\,\mathrm{kg/m^2 \cdot sec}$ one can calculate the decrease of the initial particle mass with time (or the time, which is required for certain decrease of the particle mass) from the following equation:

$$t \simeq 0.57 \frac{\Delta m}{m} \frac{\sqrt{RT}}{\gamma p a}. \tag{10}$$

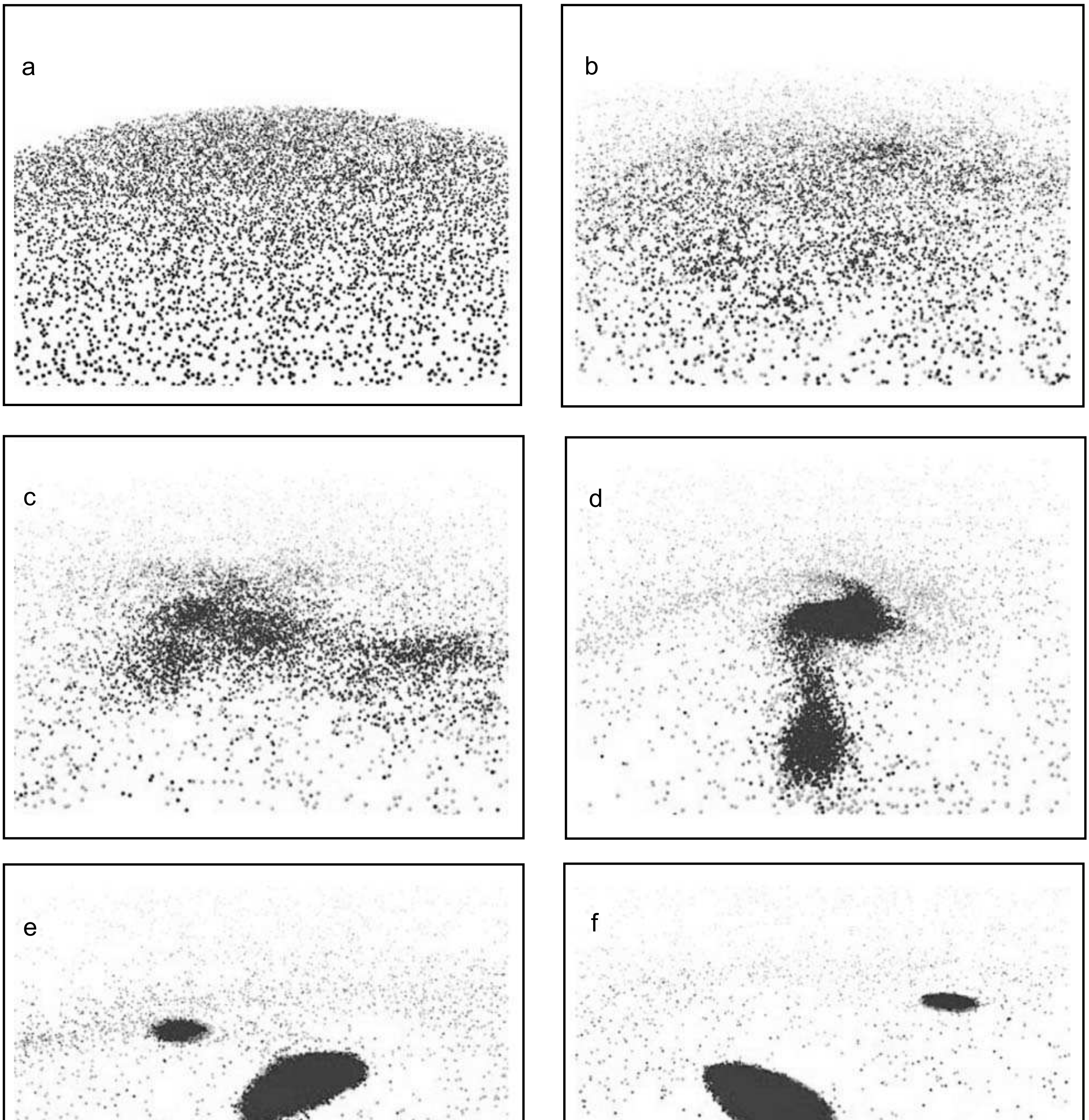

Figure 4. Computer simulation of rotational collapse of a cloud of evaporating particles (oblique projection). Number of particles is 10^4, $\omega_0/\omega_s = 0.70$. The spectral grey scale illustrates the temperature change from the lowest to the highest temperature in the system; **(a)** $t = 0$, **(b)** $t = 0.21\,T_s$, **(c)** $t = 0.41\,T_s$, **(d)** $t = 0.58\,T_s$, **(e)** $t = 0.80\,T_s$, **(f)** $t = 1.07\,T_s$, where $T_s = 2\pi/\omega_s$.

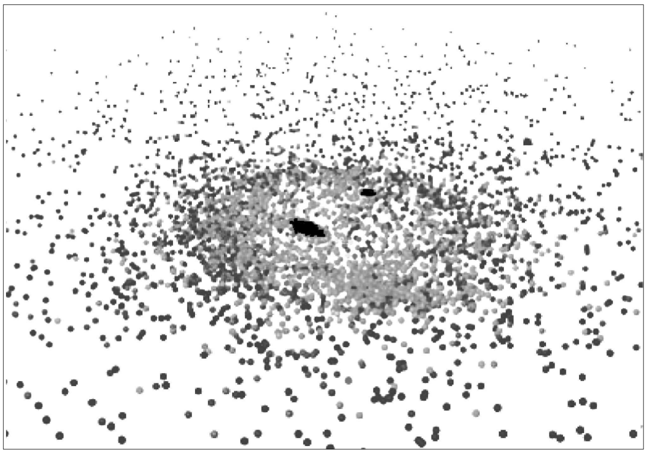

Figure 5. The cloud of particles in space surrounding the condensed bodies immediately after their formation ($t = 1.07\,T_s$).

For instance, a 40% decrease of the mass of a particle under conditions mentioned above would occur in 3×10^4 to 7×10^4 years. The period of 10^4–10^5 years can be regarded as a characteristic time of formation of a two-body system out of a dust cloud featuring the parameters of the Earth–Moon system.

The peculiar feature of our model is that the evaporation phenomenon explains both the formation of Earth–Moon double system and deficiency of iron in the Moon. As already mentioned, evaporation of particles, surrounded by their vapor, provides loss of volatiles without isotope fractionation. Table 1 shows the concentrations of main oxides in CI-chondrites, the silicate Earth and Moon, and table 2 gives the Al-normalized abundances of the corresponding elements. The relative contents of the other refractory elements Ti and Ca are identical in all the three objects. It is seen that the Moon is depleted in volatiles K and Na, as also in Fe, Si and Mg, which are usually not considered as volatiles (table 4).

The laboratory experiments have shown that Fe is a relatively volatile element. Figure 6 summarizes the experimental results of various authors, who studied variations in element concentrations during melt evaporation in vacuum (De Maria *et al* 1971; Hashimoto 1983; Markova *et al* 1986). K_2O and Na_2O are the first rock-forming components to escape from the melt. Then, the melt is depleted, in sequence, by iron, silicon and magnesium. In the course of evaporation, the melt becomes enriched in Al, Ca and Ti. The analysis of the experimental data presented in the Hashimoto experiment reveals almost quantitative correspondence between the composition of chondritic material after evaporation of 40% of the initial mass and the Moon composition. Thus the Moon's depletion in iron should be considered within the general scope of the Moon's depletion in volatile elements.

In this way, we seem to obtain a consistent physicochemical and dynamic model. A question arises, however, as to why the content of iron should be so dramatically different in the two fragments, one of which is destined to become the Earth and the other, the Moon since it is expected that both the bodies formed by fissioning of the cloud should be equally depleted in iron. The solution of the problem is assymetric growth of the embryos.

As demonstrated above, after the formation of condensed bodies, the environment still contains a large quantity of dust that is deposited onto the fragments which have already formed. The following computing experiment was therefore carried out. A particle was introduced into a system of two bodies with masses M_1 and M_2 (revolving in circular orbits) in a random way (i.e., the particle is virtually placed in an orbit around the centre of gravity) as shown in figure 7. The particle motion is calculated in the gravity field of the said bodies under the condition that $M_1 \neq M_2$. Number of particles falling on the first (n_1) and the second (n_2) body are calculated, as well as that

Table 4. *Correspondence of the composition of the Moon to the composition of the residue after evaporation of 40% of CI-material (the initial experimental data are from figure 4b).*

Component	Initial melt composition		Composition of residual melt after 40% evaporation		Moon
	Mol%	wt%	Mol%	wt%	wt%
MgO	35	23.4	45	31.9	32.0
SiO_2	35	35.0	40	42.9	43.4
FeO	27	36.9	9	15.8	13 + Fe in the core
Al + Ca*	3	4.6	6	9.4	10.8

*The total refractory components (Al_2O_3 + CaO) is taken as the difference between 100% and (Mg + SiO_2 + FeO).

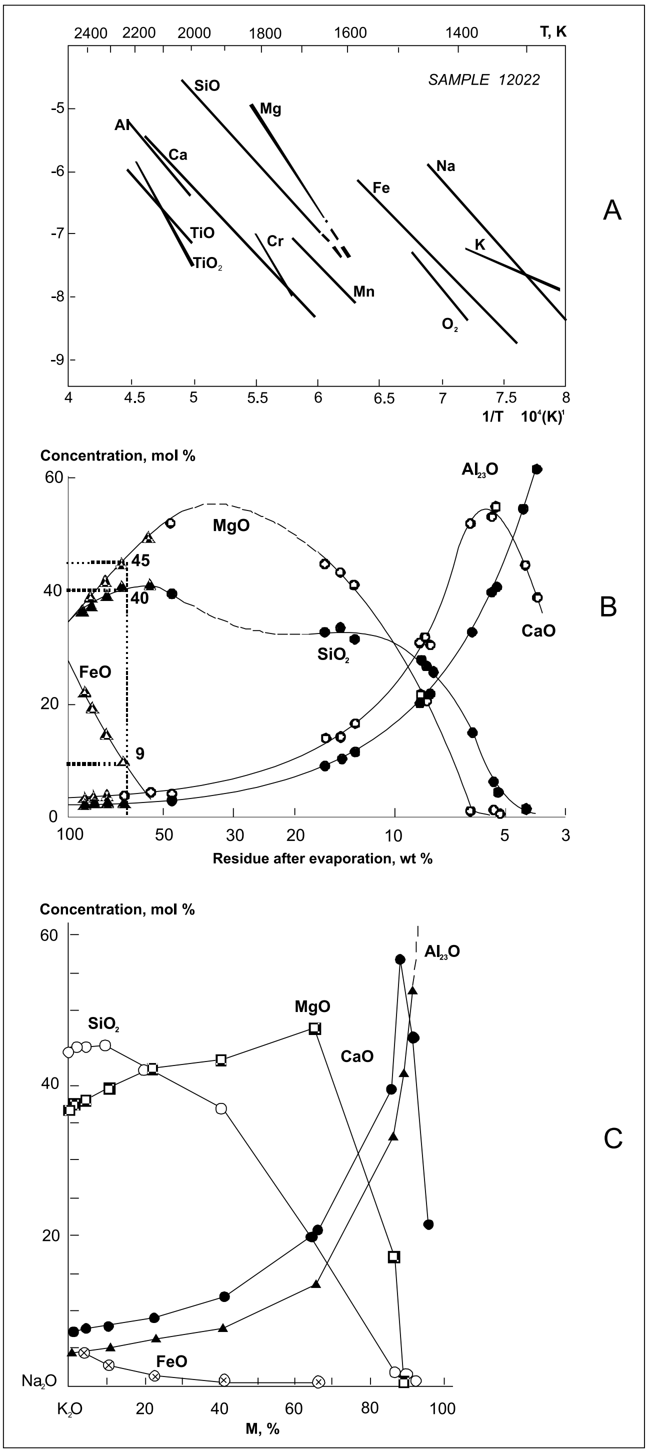

Figure 6. Experimental data for volatile loss during melt evaporation in vacuum. The data are from **(a)** De Maria *et al* (1971); **(b)** Hashimoto (1983); and **(c)** Markova *et al* (1986).

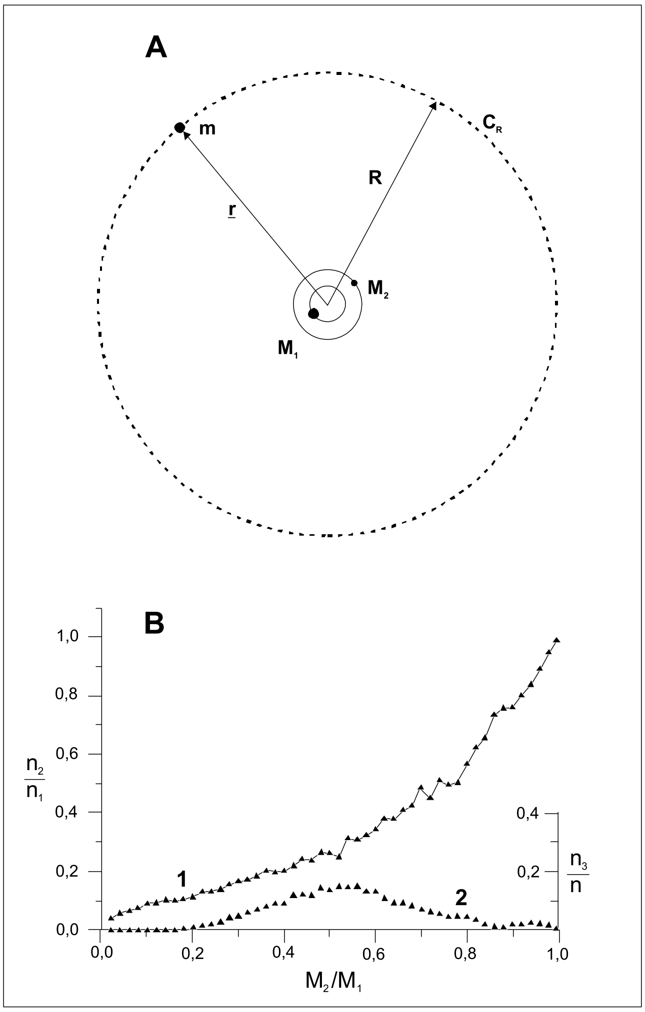

Figure 7. Simulation of the embryos growth: **(a)** the model: two embryos M_1 and M_2 rotate around the common center of mass; a particle m starts from distance R and moves in the gravitational field of the bodies; **(b)** the results of computer modeling: curve 1 is the relative number (n_2/n_1) of particles accumulated by the bodies depending on their relative masses (M_2/M_1); curve 2 is a relative mass (n_3/n) gravitationally ejected from the system $(n = 5000)$.

of particles that have flown away from the system (n_3). The results of computations are shown in figure 7. The computer simulation demonstrates that if the masses of the bodies are different, the larger body grows faster. This dependence can be closely approximated with a square function. Therefore, a random initial difference of masses leads to the situation where the smaller body does not significantly gain in mass, while the bigger one accumulates most of the initial particle pool. Thus, initially the high-temperature embryos of the Moon and the Earth were equally depleted in iron. Later on, both the Moon and the Earth acquired the colder material from the residual part of the cloud. However, the Moon accumulated little, maintaining the iron deficiency, whereas, the Earth embryo collected the major fraction of the surrounding material, whereby the composition of the Earth became closer to the composition of the cloud as a whole.

In order to avoid arbitrary numerical estimates, we used realistic parameters of the Earth–Moon system. In other words, we assumed that the collapse process developed in a cloud, the mass of which corresponded to the mass of the Earth–Moon system. Actually, it is highly probable that the separation process could take place in a smaller-size conglomeration and was followed by growth of embryos of the Earth and the Moon at the expense of the material from their orbital feed zone.

As is clear from the above arguments, we proceed with a planet accumulation model that is different from the generally accepted model (Safronov 1969; Wetherill 1980). According to the Safronov–Wetherill model, planet-size solid bodies (planetesimals) were formed in the circumsolar disk. They collided and grew in size. The Moon was a product of collision of large planet-size bodies which occurred at the final stage of planetary formation. The basic difference of our approach consists in the fact that we do not accept the possibility of primordial formation of solid bodies. However, it is also possible that the accumulation of planets or, more precisely, planet-satellite systems occurred in two stages. First, particle conglomerations are formed, accumulate and collapse. Radiation and evaporation prevented their premature consolidation. After a period, which is apparently of the order of 10^4 to 10^5 years, a collapse of primary conglomerations took place, while the largest of these conglomerations became planet embryos. At the final stage, the growth of planetary bodies might be due to their collisions with solid bodies, possibly, of asteroid size and their fragments.

We realize that many questions are open in the above discussion and some assumptions are subject to further investigation. If the suggested model of the formation of the Earth–Moon system is valid, a necessity arises for a revision of the generally accepted mechanism of accumulation of planet-satellite systems.

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