FORMATION AND GROWTH OF EMBRYOS OF THE EARTH AND THE MOON

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• ***Introduction:*** Galimov and Krivtsov [1] presented arguments that the giant impact concept [2] of the formation of the Moon has several weaknesses. They suggested that embryos of the Earth and the Moon have been formed from the same rarefied dust condensation. Below we discuss this model of formation of the Moon. Formation of massive (up to $0.1M_E$-$0.6M_E$, where M_E is the mass of the Earth) condensations was considered by several scientists (e.g. [3]). Ipatov [4-7] and Nesvorny et al. [8] supposed that trans-Neptunian satellite systems formed by contraction of rarefied condensations. In my opinion, models of formation of trans-Neptunian satellite systems and the Earth-Moon system can be similar.

Formation of embryos of the Earth and the Moon at the stage of condensations. My studies showed [9] that the angular momentum K_s used by Galimov and Krivtsov [1] in their computer simulations of the formation of the embryos of the Earth and the Moon as a result of contraction of a rarefied condensation could not be acquired during formation of the condensation from a protoplanetary disk. I obtained that **the angular momentum K_{sEM} of the present Earth-Moon system could be acquired at a collision of two rarefied condensations moving in circular heliocentric orbits with a total mass not smaller than $0.1M_E$. The mass of the rarefied condensation (formed as a result of a collision of two condensations) that was a parent for the embryos of the Earth and the Moon could be relatively small ($0.02M_E$ or even less), if we take into account the growth of the angular momentum of the embryos at the time when they accumulated planetesimals.**

• In principle, the angular momentum of the condensation needed for formation of the Earth-Moon system could be acquired by accumulation only of small objects. In this case, there could be K_s=K_{sEM} for a parental condensation with mass m>$0.2M_E$. However, for such accumulation other terrestrial planets would have large satellites. **Probably, the condensations that contracted and formed the embryos of the terrestrial planets other than the Earth did not collide with massive condensations, and therefore they did not get a large enough angular momentum needed for formation of massive satellites.**

• In our estimates of K_s discussed above, the radius of the parental condensation with the angular momentum needed for the formation of the embryos of the Earth-Moon system was comparable with the Hill radius r_H and was greater than the radius of a parental gas-dust condensation equal to **$0.023r_H$** considered in [1]**. At such small radius of the condensation, Galimov and Krivtsov [1] obtained evaporation of FeO from dust particles** and the formation of almost iron-free embryos of the Earth and the Moon. In order to get the angular momentum needed for formation of a satellite system, the condensation considered by Galimov and Krivtsov had to be a result of a compression of the condensation with a larger size than that considered in [1]. After the compression of the condensation to radius of $0.023r_H$, it could contain objects greater than dust. Some scientists (e.g., [10]) consider that condensations in the terrestrial feeding zone could consist of objects of decimeter size, which were greater than dust. **Could the above evaporation of FeO take place for decimeter size objects**, e.g. if they had fractal structure**?**

Growth of solid embryos of the Earth and the Moon. The formed solid embryos grew by accumulation of smaller objects (e.g., planetesimals). **For the case of small relative velocities of planetesimals, effective radii r_{ef} of the embryos are proportional to r^2**, where r is the radius of a considered embryo. In this case, $m_{Mo}^{-1/3}$=$m_M^{-1/3}$+$k_2m_{Eo}^{-1/3}$-$k_2m_E^{-1/3}$, where k_2=$k_d^{1/3}$, k_d is the ratio of the density of the growing Earth of mass m_E to that of the growing Moon of mass m_M (k_d≈1.65 for the present Earth and Moon), m_{Mo} and m_{Eo} are initial values of m_M and m_E. For m_M=$0.0123m_E$, m_{Eo}=$0.1m_E$, m_E=M_E the above equation is true at k_2=1 and m_{Mo}=$0.00605M_E$, and also at k_2=1.65 and m_{Mo}=$0.0054M_E$. **For such data, the mass of the Moon embryo grew by a factor of 2–2.3 while the Earth embryo grew by a factor of 10**. At r_{ef} proportional to r^2, the embryo of the Earth grew faster than that of the Moon embryo. **For large enough eccentricities of planetesimals**, **the effective radii of proto-Earth and proto-Moon were proportional to *r*.** In this case $m_{Mo}^{1/3}$=$m_M^{1/3}$+$k_1m_{Eo}^{1/3}$-$k_1m_E^{1/3}$ (where k_1=$k_d^{2/3}$) and the increase of m_M/m_{Mo} is greater than that of m_E/m_{Eo}.

• **According to Galimov and Krivtsov [1], initial embryos of the Earth and the Moon were depleted in iron**, and the Earth got a larger fraction of iron than the Moon because it grew faster by accumulation of dust. To estimate the maximum growth of m_M , let us consider the following simple model: The initial embryos didn't contain iron, and the incoming material contains 33% of iron. For a considerable growth of the mass of Earth embryo, the final fraction of iron in the embryo can be close to the present 32%. The fraction of iron in the Moon would be 0.33(1-m_{rMo}), where m_{rMo} is the ratio of the initial mass of the Moon embryo to the present mass of the Moon. Taking the present fraction of iron in the Moon to be equal to 8% and solving 0.33(1-m_{rMo})=0.08, we get m_{rMo}=0.76 and the growth of the Moon embryo by a factor of 1.3. This estimate is in accordance with the estimates by Galimov and Krivtsov [1] of the growth of the Moon embryo by a factor of 1.31 at the growth of the mass of the Earth embryo by a factor of 26.2. For the above formula, the fraction of iron in the Earth is 0.33(1-1/26.2)=0.317.

In [1] the increment dm of the embryo mass m was proportional to m^2, i.e. to r^6. At r_{ef} proportional to r^2 or to r, the growth of the Moon embryo is faster than it is needed to obtain the present fraction of iron in the Moon for growth of the Earth embryo mass by a factor of 26. May be at the gas/dust stage the relative growth of the Earth embryo was faster than at r_{ef} proportional to r^2? **For growth of the embryos of the Earth and the Moon only by direct accretion of solid planetesimals, the initial mass of the Earth embryo could not differ by an order of magnitude or more from the present mass of the Earth if we try to explain the differences in the fractions of iron in the Earth and the Moon in the above model.**

• **The Moon embryo could also grow by accumulation of almost iron-free material ejected from the Earth embryo at impacts of planetesimals with the Earth embryo**. It allows one to consider smaller (than in the above estimates) initial masses of the embryos. In the case of such accumulation, the fraction of iron in the initial embryos could be close to that in the present Earth. **This model differs from the known multiple impact models [11-13] by that the embryo of the Moon in our model was formed from the same rarefied condensation, as the Earth embryo, but not from a disk of material ejected from the Earth embryo.** The model of the formation of a solid planet with a large satellite can also work for some exoplanet.

• ***Conclusions:*** **The embryos of the Earth and the Moon could form as a result of contraction of the same parental rarefied condensation**. **A considerable fraction of the angular momentum of such condensation could be acquired at a collision of two rarefied condensations.** The present angular momentum of the Earth-Moon system could be acquired at the collision of two identical rarefied condensations with sizes of their Hill spheres, which total mass was about 0.1 of the mass M_E of the Earth and which heliocentric orbits were circular. The initial mass of the rarefied condensation that was a parent for the embryos of the Earth and the Moon could be relatively small ($0.02M_E$ or even less) if we take into account the growth of the angular momentum of the embryos at the time when they accumulated planetesimals. **The Moon embryo could get more material ejected from the Earth embryo than that fell directly on the Moon embryo.**

• There could be also the second main collision of the parental condensation with another condensation, at which the radius of the Earth's embryo condensation was smaller than the semi-major axis of the orbit of the Moon embryo. The second main collision (or a series of similar collisions) of condensations or solid bodies could change the tilt of the Earth.

• For the mass of the final condensation greater than $0.2M_E$, the angular momentum of the condensation needed for formation of the embryos of the Earth-Moon system and equal to the present momentum of the Earth-Moon system could be acquired by accumulation of small objects by this condensation. Nevertheless, a considerable fraction of the angular momentum of the final condensation probably was due to the collision of two condensations, because in the case of the large contribution of small objects and initial rotation of condensations to the final angular momentum of a parental condensation, Venus and Mars could also form with large satellites. We suppose that the angular momenta of the condensations that were parents for embryos of the terrestrial planets other than the Earth were not large enough for formation of large satellites as the Moon, because these condensations did not collide with such large condensations as the parental condensation for the Earth-Moon system did.

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