FORMATION AND GROWTH OF THE 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 supposed that solid embryos of the Earth and the Moon have been formed from the same rarefied dust condensation. Ipatov [3-6] and Nesvorny et al. [7] studied formation of trans-Neptunian satellite systems as a result of contraction of rarefied condensations. In my opinion, the model of formation of the Earth-Moon system can be similar to my model of formation of trans-Neptunian satellite systems.

Formation of solid embryos of the Earth and the Moon: The embryos of the Earth and the Moon could form as a result of contraction of the same parental rarefied condensation that got a considerable fraction of the angular momentum needed for such contraction at a collision of two rarefied condensations. The angular momentum $K_{s\mathrm{EM}}$ of the present Earth-Moon system could be acquired [8-9] at a collision of two rarefied condensations that moved before the collision in circular heliocentric orbits, if radii of the condensations are about their Hill radii and their total mass m is not smaller than $0.1M_\mathrm{E}$, where M_E is the Earth mass. As the angular momentum K_s of collided condensations is proportiomal to $m^{5/3}$, it is greater by a factor of about 46 at M_E than at $0.1M_\mathrm{E}$. The angular momentum of the final Earth-Moon system can reach $K_{s\mathrm{EM}}$ at masses of initial embryos even less than $0.01M_\mathrm{E}$ if we take into account the growth of the angular momentum of the system of the embryos at the time when they grew by accumulation of solid planetesimals. If the parental condensation with a final mass m_f grew only by accumulation of small objects, then its angular momentum could be equal to $K_{s\mathrm{EM}}$ at $m_\mathrm{f}>0.2M_\mathrm{E}$. However, for such growth of condensations only by accumulation of small objects, 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. Surville et al. [10] considered a possible formation of narrow dust disks with mass up to $0.6M_\mathrm{E}$ and the width of $(2\text{-}3)\cdot 10^{-3}$ of the distance from the Sun. Such disk could allow formation of two condensations in close orbits. There could be also the second main collision (or a series of similar collisions) of condensations or solid bodies that changed the tilt of the Earth (its present value is 23.44^o). For the second main collision of condensations, the radius of the Earth embryo condensation had to be smaller than the semi-major axis of the orbit of the Moon embryo condensation. In the case of solid objects, the mass of the impactor that produced the tilt could be about $0.01M_\mathrm{E}$.

Growth of solid embryos of the Earth-Moon system: In [8] I studied the relative growth of the embryos of the Earth and the Moon for the models for which effective radii r_{ef} of the embryos are proportional to r^2 or to r, where r is the radius of a considered embryo. In both cases it was a problem to obtain the presents fractions of iron in the Earth and in the Moon, even if initial embryos initially were depleted in iron. The present fractions of iron could be obtained only if r_{ef} was proportional to r^n with $n\geq 3$. Besides direct collisions with planetesimals, the Moon embryo could also grow by accumulation of iron-depleted material ejected from the Earth embryo at impacts of planetesimals with the Earth embryo. In the case of such accumulation, the fraction of iron in the initial embryos could be close to that in the present Earth at most values of initial masses of the embryos. In order to get the present fractions of iron in the Moon and the Earth, the mass of material ejected from the growing Earth and then acquired by the growing Moon need to exceed by an order of magnitude the sum of initial mass of iron-rich Moon embryo and the mass of iron-rich planetesimals that directly fall onto the Moon embryo. In contrast to the known multiple impact models (e.g., [11-13]), the initial embryo of the Moon in my 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.

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