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The Earth-Moon system as a typical satellite system in the Solar System

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Abstract

Trans-Neptunian satellite systems and embryos of the Earth and the Moon could be formed as a result of contraction of rarefied condensations. The angular momenta of rarefied condensations needed for such formation could be acquired at collisions of condensations. The Moon's embryo could get by an order of magnitude more material ejected from the Earth's embryo than that fell directly onto the Moon's embryo.

1. Formation of trans-Neptunian satellite systems and embryos of the Earth-Moon system at a stage of rarefied condensations

It is considered by many scientists that solid planetesimals were formed by contraction of rarefied condensations, which consisted of dust and/or boulders with diameter up to 1 m [1]. Formation of trans-Neptunian satellite systems as a result of contraction of rarefied condensations was discussed in [2-5]. Ipatov [3] showed that the angular velocities of condensations used by Nesvorny et al. [4] as initial data for computer simulations of contraction of rarefied condensations leading to the formation of satellite systems of trans-Neptunian objects could be obtained at collisions of condensations, which moved before collisions in almost circular heliocentric orbits. Such considered model of the formation explains well the observed dependences of the orbital elements and masses of the components of binary trans-Neptunian objects [5]. The initial angular momenta of the condensations are not sufficient for the formation of satellite systems of small bodies. The angular momentum acquired by the condensation at its growth due to accumulation of small objects is positive at small eccentricities of their heliocentric orbits, while about 40% of trans-Neptunian satellite systems have negative angular momenta. The sign of the angular momentum at a collision of condensations depends on the parameters of the collision [2-3].

In my opinion, models of formation of trans-Neptunian satellite systems and of formation of the Earth-Moon system can be similar. The angular momentum of the condensation used by Galimov and Krivtsov [6] in their computer simulations of compression of the condensation leading to the formation of embryos of the Earth and the Moon could be obtained [7] at a collision of two condensations. I showed that the angular momentum of the present Earth-Moon system could be acquired at a collision of two rarefied condensations with a total mass not smaller than $0.1M_E$, where M_E is the mass of the Earth. The mass of the condensation that was a parent for the embryos of the Earth and the Moon could be relatively small ($\sim 0.01M_E$), if we take into account the growth of the angular momentum of the embryos at the time when they accumulated solid planetesimals. If the condensation grew by accumulation only of small objects, then the angular momentum of the present Earth-Moon system could be acquired for a parental condensation with mass $m > 0.2M_E$. However, for such accumulation of only 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. [8] considered a possible formation of narrow dust disks with mass up to $0.6M_E$ 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. For the second main collision of condensations, the radius of the Earth's embryo condensation had to be smaller than the semi-major axis of the orbit of the Moon's embryo. In the case of solid objects, the mass of impactor that produces the tilt could be about $0.01M_E$.

2. Growth of the Moon's embryo

For my computer simulations of migration of planetesimals in the forming Solar System, the probabilities of collisions of planetesimals with a celestial object calculated per mass of the object were greater for the Moon than for the Earth. However, at such collisions, more material was ejected from the Moon than from the Earth. Besides direct collisions with planetesimals, the Moon's embryo also grew by accumulation of iron-depleted material ejected from the Earth's embryo at impacts of planetesimals with the Earth's embryo. If the iron abundance in the initial Moon's embryo and in planetesimals was 0.33 and the iron abundance in the crust of the Earth and on the Moon was 0.05 and 0.08, respectively, then the fraction k_E of matter of the Earth's crust in the Moon should be about 0.9 (this follows from the relation $0.05k_E+0.33(1-k_E)=0.08$). The greater fraction of matter incorporated into the Moon's embryo could be ejected from the Earth in its multiple collisions with planetesimals (and smaller bodies). This model differs from the known multiple impact models (e.g., [9]) by that the initial embryo of the Moon in my model was formed from the same rarefied condensation, as the Earth's embryo, but not from a disk of material ejected from the Earth's embryo. The previous multiple impact models do not explain clearly why only the Earth, but not other terrestrial planets, formed with a large satellite. In my model, it is not needed to form the initial Moon's embryo from material ejected from the Earth. The model of the formation of a solid planet with a large satellite can also work for some exoplanet.

Summary and Conclusions

Trans-Neptunian satellite systems and embryos of the Earth-Moon system could be formed as a result of contraction of rarefied condensations. The angular momenta of rarefied condensations needed for such formation could be acquired at collisions of condensations. The angular momentum of the present Earth-Moon system could be acquired at a collision of two rarefied condensations with a total mass not smaller than $0.1M_E$. The mass of the condensation that was a parent for the embryos of the Earth and the Moon could be about $0.01M_E$, if we take into account the growth of the angular momentum of the embryos with growth of their masses. The Moon's embryo could get by an order of magnitude more material ejected from the Earth's embryo than that fell directly onto the Moon's embryo.

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