Origins: From the Protosun to the First Steps of Life
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Formation of the Earth-Moon system

Sergei I. Ipatov

Vernadsky Institute of Geochemistry and Analytical Chemistry of RAS,
119991, 19 Kosygin st., Moscow, Russia
email: siipatov@hotmail.com

Abstract. 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 $0.1M_E$, 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 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 embryo could get by an order of magnitude more material ejected from the Earth embryo than that fell directly onto the Moon embryo.

Keywords. methods: n-body simulations, Earth, Moon, solar system: formation

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1. Introduction

Galimov & Krivtsov (2012) presented arguments that the popular giant impact concept (e.g., Canup *et al.* 2013) of the formation of the Moon has several weaknesses. They suggested that solid embryos of the Earth and the Moon have been formed from the same rarefied dust condensation. Formation of massive (up to $0.1M_E - 0.6M_E$, where M_E is the mass of the Earth) condensations was studied by several scientists (e.g. Lyra *et al.* 2008). Surville *et al.* (2016) considered a possible formation of a narrow dust disk with a mass up to $0.6M_E$ and the width of $(2-3)10^{-3}$ of the distance from the Sun. Ipatov (2010, 2014, 2017a,b) and Nesvorny *et al.* (2010) studied formation of trans-Neptunian satellite systems as a result of contraction of rarefied condensations. In my opinion, the model of formation of trans-Neptunian satellite systems and that of formation of the Earth-Moon system can be similar.

2. Formation of solid embryos of the Earth-Moon system at the stage of rarefied condensations

Ipatov (2014, 2017a) showed that the angular momentum of a condensation needed in calculations by Nesvorny *et al.* (2010) for formation of a satellite system could be acquired at a collision of two condensations moved around the Sun in circular orbits. The radii of the condensations did not differ much from their Hill radii. The angular momentum K_{sEM} of the present Earth-Moon system could be acquired at a collision of two rarefied condensations with radii about their Hill radii and with a total mass not smaller than $0.1M_E$ (Ipatov 2015, 2018a). The mass of the condensation that was a parent for the embryos of the Earth and the Moon could be relatively small ($0.01M_E$ or even less), if we take into account the growth of the angular momentum of the embryos with growth of their masses. The angular momentum K_s of the condensation used by Galimov & Krivtsov (2012) in their computer simulations of the formation of the embryos of the

Earth-Moon system as a result of contraction of a rarefied condensation could not be acquired during formation of the condensation from a protoplanetary disk.

Some fraction of the angular momentum of the parental condensation could be acquired by its accumulation of small objects. If we consider accumulation only of small objects, then $K_s = K_{sEM}$ for a parental condensation with mass $m > 0.2M_E$. However, for such accumulation of only small objects, other terrestrial planets could have large satellites because their parental condensations also could get the angular momenta needed for formation of satellites. On the other hand, large concentration of matter could be only at 1 AU. Probably, the condensations that contracted and formed the embryos of the terrestrial planets other than the Earth did not collide with similar massive condensations, and therefore they did not get a large enough angular momenta needed for formation of massive satellites. 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 embryo condensation had to be smaller than the semi-major axis of the orbit of the Moon embryo condensation. Note that for two condensations with masses equal to $0.01M_E$ moved in circular close orbits with semimajor axes about 1 AU, their typical collision would be in about 100 yrs. During this time the condensations could approximately keep their original sizes.

3. Growth of solid embryos of the Earth-Moon system

First let us consider the model for which the solid embryos of the Earth-Moon system that formed from the parental condensation both grew only by accumulation of smaller objects from the same source. In 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,

$$m_{Mo}^{-1/3} = m_M^{-1/3} + k_2 m_{Eo}^{-1/3} - k_2 m_E^{-1/3}, \tag{1}$$

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 ($k_d \approx 1.65$ for the present Earth and Moon), m_{Mo} and m_{Eo} are initial values of m_M and m_E. From equation (1) one can obtain that 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 $r_{ef} \propto r^2$, the embryo of the Earth grew faster than that of the Moon. For large enough eccentricities of planetesimals, the effective radii of proto-Earth and proto-Moon were proportional to r. In this case

$$m_{Mo}^{1/3} = m_M^{1/3} + k_1 m_{Eo}^{1/3} - k_1 m_E^{1/3} \tag{2}$$

(where $k_1 = k_d^{2/3}$) and the increase of m_M/m_{Mo} is greater than that of m_E/m_{Eo}.

Galimov & Krivtsov (2012) supposed that 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 fraction of iron in the initial embryos is denoted by β, and the incoming material contained 33% of iron. The fraction of iron in the Moon would be equal to $0.33 + (\beta - 0.33)m_{rMo}$, 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 $0.33 + (\beta - 0.33)m_{rMo})$=0.08, we get $m_{rMo} \geqslant 0.76$ and the growth of the Moon embryo mass by a factor of not more than 1.3. As $m_{rMo} \leqslant 1$, then this equation can be solved only for $\beta \geqslant 0.08$. At r_{ef} proportional to r^2 from formula (1), one can obtain that for the growth of the mass of the Moon embryo from $M_M/1.3$ to the present mass M_M of the Moon, the mass of the Earth embryo grew (to M_E) by a factor of 2.4 or 2.7 at k_d equal to 1.65 and 1, respectively. In this case for the above simple model, the fraction of iron in the Earth did not exceed 0.33(1-1/2.7)≈0.21 and was less than the present value equaled to 0.32. In order to obtain the current iron content in the Earth and the Moon, the increment dm of the embryo mass should be proportional to m^p, where $p \geqslant 2$, as it was considered by Galimov & Krivtsov (2012). For the motion of solid bodies in a gas-free medium, parameter p does not exceed 4/3. In my opinion, if the embryos are assumed to have grown only by accumulation of solid planetesimals (without the ejection of matter from the embryos), it is hard to reproduce the current lunar and terrestrial iron abundances at any initial abundance in the embryos.

Besides direct collisions with planetesimals, the Moon embryo should also grew by accumulation of iron-depleted material ejected from the Earth embryo at impacts of planetesimals with the Earth embryo. If the iron abundance in the initial Moon 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, than the fraction k_E of matter of the Earth 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 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., Rufu & Aharonson 2017) by that 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 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 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.

Based on our runs of migration of planetesimals from the feeding zone of Jupiter and Saturn (Marov & Ipatov 2018) and from different distances from the Sun (from 5 to 40 AU) (Ipatov 2018b) and of migration of Jupiter-crossing objects (Ipatov & Mather 2007), I calculated probabilities of collisions of such planetesimals and objects with the Moon. Such probabilities were typically smaller than the probabilities of collisions with the Earth by a factor of 16 or 17 for the planetesimals and many Jupiter-family comets. For some Jupiter-family comets, the factor was up to 25. Based on the above results, we can conclude that the amount of the material, including water, collided with the Moon and migrated from outside of the Jupiter's orbit could be smaller by about a factor of 20 than that delivered to the Earth from this region. However, a greater fraction of water could be evaporated at such collisions for the Moon than for the Earth.

I also studied the migration of planetesimals from different regions of the feeding zone of the terrestrial planets and the probabilities of their collisions with these planets or their embryos. When the embryos were small, they accumulated planetesimals from their neighbourhood. For masses of the embryos close to masses of the terrestrial planets, for different source regions of the planetesimals, the fraction of planetesimals collided with Earth differed by less than a factor of 2 from that with Venus. The ratio of planetesimals collided with the Earth to those collided with the Moon was about 35 for planetesimals initially moved in low eccentric orbits near the Earth's orbit and was about 25 for more distant regions of the feeding zone of the terrestrial planets. In calculations with masses and orbits of planets close to their present values, most of planetesimals collided with the Earth and the Moon mainly in 20 Myr both for planetesimals from the feeding zone of the terrestrial planets and from initial distances between 5 and 30 AU. However, some planetesimals from the feeding zones of Uranus and Neptune could collide the Earth and the Moon after hundreds of Myrs.

4. 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 ($0.01M_E$ or even less) if we take into account the growth of the angular momentum of the embryos during growth of masses of the embryos. The Moon embryo could get by an order of magnitude more material ejected from the Earth embryo than that fell directly onto the Moon embryo.

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Discussion

GÜDEL: You mentioned that planetary tilt may be due to early collisions. But wouldn't tilt vary in later evolution due to perturbations?

IPATOV: Two condensations that formed in the parental condensation could move one above another (not in one plane). The angular momentum of the formed condensation could be not perpendicular to ecliptic. During accumulation of planetesimals, the Earth embryo's angular momentum became more perpendicular to the ecliptic, but some tilt remained.