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

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Abstract

The minimum value of the mass of the rarefied condensation that was a parent for the embryos of the Earth and the Moon could be about 0.02 of the Earth mass. There could be also another main collision of the parental condensation with another condensation, which changed the tilt of the Earth to its present value. Depending on eccentricities of planetesimals that collided with solid embryos of the Earth and the Moon, the Moon could acquire 0.04-0.3 of its mass at the stage of accumulation of solid bodies while the mass of the growing Earth increased by 10 times.

1. Introduction

Galimov and Krivtsov [1] noted that the giant impact concept, which is a popular model of the Moon formation, has several weaknesses. In particular, they calculated formation of the Earth-Moon system from a rarefied protoplanet. Lyra et al. [4] showed that in the vortices launched by the Rossby wave instability in the borders of the dead zone, the solids quickly achieve critical densities and undergo gravitational collapse into protoplanetary embryos in the mass range 0.1-0.6M_E (where M_E is the mass of the Earth). Ipatov [2] and Nesvorny et al. [5] supposed that transneptunian satellite systems have been formed from rarefied condensations. It was shown in [2] that the angular momenta acquired at collisions of condensations moved in circular heliocentric orbits could have the same values as the angular momenta of discovered transneptunian and asteroid binaries. Ipatov [3] obtained that the angular momenta used in [5] as initial data in calculations of the contraction of condensations leading to formation of transneptunian binaries could be acquired at collisions of two condensations moved in circular heliocentric orbits. I supposed that the number of collisions of condensations at which the formed condensation with mass equal to that of a solid body with diameter d>100 km got the angular momentum needed for formation of a satellite system can be about or a little greater than the number of small bodies with d>100 km having satellites (among all such small bodies), i.e., the fraction of condensations formed at such collisions among all condensations can be about 0.3 for objects formed in the transneptunian belt. The model of collisions of condensations explains negative angular momenta of some observed binaries, as about 20 percent of collisions of condensations moving in circular heliocentric orbits lead to retrograde rotation.

2. The angular momentum at a collision of two rarefied embryos

Using the formulas presented in [2], we obtained the angular momentum of the Earth-Moon system could be acquired at a collision of two rarefied condensations with a total mass not smaller than 0.1M_E. We suppose that solid proto-Earth and proto-Moon could be formed by contraction of a condensation (e.g., according to the models of contraction of a condensation presented in [1, 5]). In calculations of contraction of condensations (of mass m and radius r equal to 0.6 of the Hill radius) presented in [5], satellites were formed at initial angular velocities ω_o from the range $0.5\Omega_o$–$0.75\Omega_o$, where $\Omega_o=(Gm/r^3)^{1/2}$ (G is the gravitational constant). In 3-D calculations of gravitational collapse of a condensation presented in [1], binaries were formed at ω_o/Ω_o from the range of 1-1.46. For smaller ω_o/Ω_o, satellites were not formed. At a collision of two condensations, the angular velocity can be as high as $0.9\Omega_o$ [2]. Collided condensations could have some angular momenta before the collision. So in principle the resulting angular velocity of the formed condensation can exceed $0.9\Omega_o$. The difference in results presented in [1] and [5] can be caused, in particular, by different chaotic velocities of particles/bodies constituting condensations and by different sizes of condensations. The radii of condensations in calculations presented in [1] were smaller (e.g. by about a factor of 40 than the Hill radii for the example presented on page 108 in [1]). Therefore any initial angular velocities considered in [1] can be reached after contraction of the condensation formed at a collision of condensations close to Hill spheres (the angular velocity of a compressed condensation of radius r_c formed from a condensation with the Hill radius r_H and the angular velocity ω_H, equals $\omega_{rc}=\omega_H(r_H/r_c)^2$ [2]). 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, but for such model, the parental condensations of Venus and Mars could also get large angular momentum, which was enough for formation of large satellites.

3. Relative growth of solid embryos of the Earth and the Moon

Let us consider the model of the growth of the solid proto-Earth and proto-Moon to the present masses of the Earth and the Moon (M_E and $0.0123M_E$, respectively) by accumulation of smaller planetesimals for the case when the effective radii of proto-Earth and proto-Moon are proportional to r (where r is the radius of a considered embryo). Such proportionality can be considered for large enough eccentricities of planetesimals. In this case, based on $dm_M/m_M=k\cdot(m_M/m_E)^{2/3}dm_E/m_E$ we can obtain $r_{Mo}=m_{Mo}/M_E=[(0.0123^{-2/3}-k+k\cdot(m_{Eo}/M_E)^{-2/3})]^{-3/2}$, where $k=k_d^{-2/3}$, k_d is the ratio of the density of the growing Moon of mass m_M to that of the growing Earth of mass m_E ($k_d=0.6$ for the present Earth and Moon), m_{Mo} and m_{Eo} are initial values of m_M and m_E. For $r_{Eo}=m_{Eo}/M_E=0.1$, we have $r_{Mo}=0.0094$ at $k=1$ and $r_{Mo}=0.0086$ at $k=0.6^{-2/3}$. At these values of r_{Mo}, the ratio $f_m=(0.0123-r_{Mo})/0.0123$ of the total mass of planetesimals that were accreted by the Moon at the stage of the solid body accumulation to the present mass of the Moon is 0.24 and 0.30, respectively. In this case for the growth of the mass of the Earth embryo by 10 times, the mass of the Moon embryo increased by a factor of 1.31 and 1.43, respectively.

If we consider that effective radii of the embryos are proportional to r^2 (the case of small relative velocities of planetesimals), then integrating $dm_M/m_M=$ $=k_2\cdot(m_M/m_E)^{4/3}dm_E/m_E$, we can get $r_{Mo2}=m_{Mo}/M_E=$ $=[(0.0123^{-4/3}-k_2+k_2\cdot(m_{Eo}/M_E)^{-4/3})]^{-3/4}$, where $k_2=k_d^{-1/3}$. In the case of $r_{Eo}=m_{Eo}/M_E=0.1$ we have $r_{Mo}=0.01178$ at $k_2=1$ and $r_{Mo}=0.01170$ at $k_2=0.6^{-1/3}$, and f_m equals 0.042 or 0.049, respectively. In this case for the growth of the Earth embryo mass by 10 times, the Moon embryo mass increased by the factor of 1.044 and 1.051 at $k_2=1$ and $k_2=0.6^{-1/3}$, respectively. In the above model depending on eccentricities of planetesimals, the Moon could acquire 0.04-0.3 of its mass at the stage of accumulation of solid bodies during the time when the mass of the growing Earth increased by a factor of ten. Probably, the condensations that contracted and formed the embryos of other terrestrial planets did not collide with massive condensations, and therefore they did not get a large enough angular momentum needed to form massive satellites.

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. In this case, the angular momentum of the Earth and the Moon that have grown from the embryos could be the same as that for the real Earth-Moon system. 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's embryo. The second main collision (or a series of similar collisions) could change the tilt of the Earth to its present value.

References

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