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Formation and growth of embryos of the Earth and the Moon

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Abstract

The model of the formation of the embryos of the Earth and the Moon as a result of contraction of the same parental rarefied condensation is discussed. The angular momentum of the condensation needed for such formation could be mainly acquired at the collision of two rarefied condensations at which the parental condensation formed.

Introduction

Many authors suppose that the Earth-Moon system formed as a result of a collision of the solid Earth with a Mars-size object. Galimov and Krivtsov [1] presented arguments that the giant impact concept has several weaknesses. Lyra et al. [2] 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 $0.1M_E$-$0.6M_E$ (where M_E is the mass of the Earth). Ipatov [3-5] and Nesvorny et al. [6] supposed that trans-Neptunian satellite systems formed by contraction of rarefied condensations.

1. Formation of the embryos of the Earth and the Moon at the stage of condensations

Galimov and Krivtsov [1] made computer simulations of the formation of the embryos of the Earth and the Moon as a result of contraction of a rarefied condensation. The angular momentum K_s needed for such contraction could not be acquired during formation of the condensation from a protoplanetary disk. Using the formulas presented in [2], we obtained that the angular momentum K_{sEM} of the present Earth-Moon system could be acquired at a collision of two rarefied condensations with a total mass not smaller than $0.1M_E$. 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, if K_s of parental condensations for all embryos of terrestrial planets grew only during accumulation of small objects by the condensations, then all these 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. The embryos formed as a result of contraction of the condensation grew by accumulation of solid planetesimals. The 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 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 dust condensation, Galimov and Krivtsov [1] obtained evaporation of iron 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., [7]) consider that condensations in the terrestrial feeding zone could consist of objects of decimeter size, which were greater than dust.

2. Growth of solid embryos of the Earth and the Moon

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 $k_2=k_d^{4/3}$, 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 ($k_d\approx1.65$ 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 $m_{Mo}=0.0035M_E$. For such data, the mass of the Moon grew by a factor of 2 – 3.5 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. For large enough eccentricities of planetesimals, the effective radii of proto-Earth and proto-Moon were proportional to r. In this case $m_{Mo}^{1/3}=m_M^{1/3}+k_1m_{Eo}^{1/3}-k_2m_E^{1/3}$ (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 almost free from iron, and the Earth got more iron than the Moon because it grew faster by accumulation of dust. 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 $0.33(1-m_{rMo})$, где 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 $0.33(1-1/26.2)=0.317$. 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 Earth embryo by accretion of solid planetesimals, its initial mass 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.

Note that one more collision (or a series of collisions) of a parental condensation or a solid Earth embryo with a massive object is needed to change the tilt of the Earth to its present value. It could be at the stage of solid embryos or at the stage of condensations if at a collision the radius of the Earth embryo condensation was smaller than the semi-major axis of the orbit of the Moon embryo condensation around the Earth embryo condensation.

I suppose that the problem of formation of iron-free embryos as a result of compression of a condensation need to be more clarified, e.g. for the case when the parental condensation consisted of larger objects than dust. May be the objects had fractal structure and their evaporation was close to that considered in [1]? The model of the formation of a solid planet with a large enough satellite can work for some exoplanet.

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