THE ROLE OF COLLISIONS OF RAREFIED CONDENSATIONS IN FORMATION OF EMBRYOS OF THE EARTH AND THE MOON.
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Introduction: Many authors suppose that the Earth-Moon system formed as a result of a collision of the solid Earth with a Mars-sized object. Galimov and Krivtsov [1] presented arguments that the giant impact concept has several weaknesses. In particular, they calculated the formation of the embryos of the Earth-Moon system from a rarefied protoplanet and studied the growth of the solid embryos of the Earth and the Moon by accumulation of dust. 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 [3-4] and Nesvorny et al. [5] supposed that trans-Neptunian satellite systems formed by contraction of rarefied condensations. Below we discuss that the formation of the Earth-Moon system from a rarefied condensation can be considered similar to formation of trans-Neptunian binaries, and the Earth-Moon system can be a typical binary in the Solar System.

Initial Angular Velocities of Rarefied Condensations and Angular Velocities Needed for Formation of Satellite Systems: According to Safronov [6], the initial angular velocity of a rarefied condensation (around its center of mass) was 0.2Ω for a spherical condensation, where Ω is the angular velocity of the condensation moving around the Sun. The initial angular velocity is positive and is not enough for formation of satellites. In calculations of contraction of condensations (of mass m and radius $r=0.6r_H$, where r_H is the Hill radius) presented in [5], trans-Neptunian objects with satellites formed at initial angular velocities ω_o from the range of $0.5\Omega_o$–$0.75\Omega_o$, where $\Omega_o=(Gm/r^3)^{1/2}$, G is the gravitational constant. As $\Omega_o/\Omega\approx1.73(r_H/r)^{3/2}$, then $\Omega\approx0.58\Omega_o$ and $0.2\Omega\approx0.12\Omega_o$ at $r=r_H$. At $r=0.6r_H$, $\Omega\approx0.27\Omega_o$ and $0.2\Omega\approx0.054\Omega_o$.

In the 3D calculations of gravitational collapse of a condensation presented in [1], binaries formed at ω_o/Ω_o from the range of 1-1.46. The radii of initial condensations used in calculations considered in [1] were much smaller (by about a factor of 40) than their Hill radii. In their model, Galimov and Krivtsov [1] need to consider evaporation of particles that constitute a rarefied condensation in order to explain the formation of the Earth-Moon system from the condensation with the same angular momentum as that of this system. May be if they consider another size of the condensation in their calculations, then they will get the Moon in the model without the evaporation. It may be interesting to make calculations of contraction of condensations for a wider range of ratios of sizes of condensations to their Hill radii than in calculations presented in [1,5].

The Angular Momentum at a Collision of Two Condensations: Ipatov [4] showed that the angular velocity ω of the condensation formed at the collision of two identical condensations moving in circular heliocentric orbits can be as high as 1.575Ω. At $r=r_H$, ω can be as high as $0.9\Omega_o$, or even a little greater than Ω_o, if we take into account the initial 0.2Ω. Ipatov [4] noted that the angular momentum obtained at the collision is enough for formation of a satellite system in the model considered in [5]. The angular velocity obtained at the collision is a little smaller than Ω_o needed for formation of binaries in calculations by Galimov and Krivtsov [1], but contraction of the condensation formed at the collision to the condensation considered in [1] can considerably increase the angular velocity. The angular velocity of a condensation of radius r_c formed as a result of compression of the condensation, with radius r_1 and the angular velocity ω_1, equals $\omega_{rc}=\omega_1(r_1/r_c)^2$. The angular momentum of the condensation of radius $0.12r_H$ formed at a typical collision of two identical condensations is the same as the angular momentum for the condensation with $r=0.025r_H$ considered in [1]. Therefore, any initial angular velocities considered in [1,5] can be reached after contraction of the condensation formed at a collision of condensations not greater than their Hill spheres.

The Angular Momentum of a Rarefied Condensation Formed by Accumulation of Smaller Objects: For the growth of a rarefied condensation of mass m and radius r by accumulation of smaller objects the angular momentum is $K_s\approx0.173k_H^2G^{1/2}a^{1/2}m^{5/3}M_S^{-1/6}\Delta K$ [3], where $r=k_Hr_H$, a is a semi-major axis of the condensation, M_S is the mass of the Sun, ΔK is the difference between the fraction of positive increments of angular momentum and the fraction of negative increments. At $\Delta K=0.9$ (a typical value for Hill spheres in circular heliocentric orbits), $m=M_E+M_M$ (the sum of present masses of the Earth and the Moon), $k_H=1$, and $a=1$ AU, we obtain that K_s is greater by a factor of 24.5 than the present angular momentum K_{sEM} of the Earth-Moon system, including the rotational momentum of the Earth. Taking into account that K_s is proportional to $m^{5/3}$, we obtain that $K_s=K_{sEM}$ at $m=(M_E+M_M)/6.8$. The angular momentum of the Earth-Moon system is positive. Therefore, for the mass of the final condensation $m \geq 0.15M_E$, the angular momentum equal to K_{sEM} can be acquired at any contribution of a collision of two large condensations to the angular momentum of the final condensation. 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 we suppose that the collision of condensations played a considerable role in the angular momentum of the collapsing condensation because else Venus and Mars could also born with large satellites as their parent condensations could get large angular momentum. The greater was the role of small objects in formation of the condensation that was a parent for the Earth-Moon system, the smaller could be the mass of the smaller collided condensation at the main collision. It may be a question whether two condensations which masses differed by an order of magnitude could form at close distances from the Sun. Dust particles and bolders could considerably change distances from the Sun with time and could reach the growing condensation from not close distances if the lifetime of the condensation was not small. In order to get large times of contraction of condensations, it is needed to consider factors preventing fast collapse of condensations. In the models of contraction of condensations considered by Myasnikov and Titarenko [7-8], lifetimes of gas-dust condensations could exceed several Myrs and depended on optical properties of the material and on concentration of short-lived radioactive isotopes.

The Growth of Solid Embryos of the Earth and the Moon: Let us consider the model of the growth of solid embryos of the Earth and the 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_e (where r_e 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 a factor of ten, 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_e^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 $k_2=k_d^{-1/3}$. For $r_{Eo}=m_{Eo}/M_E=0.1$, we have $r_{Mo}=0.01178$ and $f_m=0.042$ at $k_2=1$, and $r_{Mo}=0.01170$ and $f_m=0.049$ at $k_2=0.6^{-1/3}$. 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 (the lower estimate is for almost circular heliocentric orbits) 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 initial mass of a solid proto-Earth could exceed $0.1M_E$, and so the growth of the Moon embryo could be smaller than the estimate obtained for the growth of the mass of the Earth embryo by a factor of ten.

In our model the influx of the matter to embryos is from the zone around the heliocentric orbit of the Earth-Moon embryos system, but not only from the sphere around the embryos as in [1]. For comparison with [1], in the case of k_d=0.6 at M_E/m_{Eo}=26.2 we have $M_M/m_{Mo}\approx 2$ at r_{ef} proportional to r_e and $M_M/m_{Mo}\approx 1.19$ at r_{ef} proportional to r_e^2, i.e., their estimates ($M_M/m_{Mo}\approx 1.31$) are close to our considered model at r_{ef} proportional to r_e^2. At M_E/m_{Eo}=5 and k_d=0.6, the range of values of M_M/m_{Mo} is (1.019, 1.224) for r_{ef} proportional to r_e^2 and r_e, respectively.

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