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. 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 Ω_o=$(Gm/r^3)^{1/2}$, G is the gravitational constant. As Ω_o/Ω≈$1.73(r_H/r)^{3/2}$, then Ω≈$0.58\Omega_o$ and 0.2Ω≈$0.12\Omega_o$ at r=r_H. At r=$0.6r_H$, Ω≈$0.27\Omega_o$ and 0.2Ω≈$0.054\Omega_o$.

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.

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 ω_{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 of 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≈$0.173k_H^2G^{1/2}a^{1/2}m^{5/3}M_S^{-1/6}\Delta K$ [3], where r=k_Hr_H, a is the 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 ΔK=0.9 (a typical value for Hill spheres moving 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≥$0.15M_E$, 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.

Models of 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 results by Galimov and Krivtsov [1], in the case of k_d=0.6 at M_E/m_{Eo}=26.2 we have M_M/m_{Mo}≈2 at r_{ef} proportional to r_e and M_M/m_{Mo}≈1.19 at r_{ef} proportional to r_e^2, i.e., their estimates (M_M/m_{Mo}≈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.

Discussion

We suggest the following scenario of the Earth-Moon formation: We suppose that the condensation that was a parent for embryos of the Earth and the Moon formed as a result of the first main collision of two condensations that did not differ much in masses. The angular momentum of the parental condensation was almost perpendicular to the ecliptic plane. A few other collisions of the parental condensation with smaller condensations could increase the momentum in this direction. Two rarefied embryos formed from the parental condensation. After the radius of the contracting embryo of the Earth became less than the semi-major axis of the Moon's embryo, there could be a collision of the Earth's rarefied embryo with another condensation. At this 'second main' collision, the component of the angular momentum in the direction located in the ecliptic plane could be smaller by a factor of about 10 than the value of the angular momentum which was perpendicular to the ecliptic and had been acquired before the second main collision. At the second main collision, the collided condensations could move one above another (not at the same plane), and the ratio of their radii to the Hill radii could be smaller by a factor of several than at the first main collision (K_s is proportional to the sum of radii of collided condensations). In principle, there could be other collisions of the rarefied Earth's embryo with smaller condensations, which increased the component of the angular momentum of the Earth's embryo that was located in the ecliptic plane.

In the case of collisions of solids objects, masses of impactors needed for the above explanations of the formation of the two components of the vector of the angular momentum should be much greater than in the case of collisions of rarefied condensations, i.e., two giant impacts are needed. The component of the angular momentum equal to 2.3×10^{33} kg m^2 sec^{-1} (and located in the ecliptic plane) could be acquired at the collision of the Earth with an object of mass m_i=$0.1M_E$ at a tangential velocity v_i=6.7 km sec^{-1} (or at any other values of m_i and v_i with the same value of m_iv_i). Such velocity corresponds to the eccentricity of a heliocentric orbit of about 0.2. The large impactor which explains the axial tilt of the Earth was considered by Safronov (1969) and several other scientists. This tilt cannot be explained if we consider only the fall of small planetesimals onto the Earth (or only the growth of the parental rarefied condensation by accumulation of smaller objects).

The absence of large satellites of the terrestrial planets other than the Earth can be caused by that their parental condensations did not collide with such large condensations as the Earth's parental condensation did, and therefore their parental condensations did not get large enough angular momenta that were needed for formation of large satellites. The axial tilt of Mars (25°) could be caused by the collision of Mars's parental condensation with a smaller condensation. Both condensations could be smaller than their Hill spheres and did not move in the same plane. Such collision allowed the parental condensation to get the component of the angular momentum located in the ecliptic plane. The angular momentum at the main collision of the Venus's parental condensation with another condensation could be negative, and its absolute value could be greater than the sum of positive initial angular momentum and positive increments caused by collisions of the parental condensation with smaller condensations and other objects. The final angular momentum of Venus is negative, and its absolute value is much smaller than that for the Earth-Moon system. It is almost perpendicular to the ecliptic plane. Such direction of the angular momentum could be caused by that at the main collision, condensations moved almost in the same plane. May be the Mercury's parental condensation did not collide with other large condensations, and therefore Mercury's angular velocity is relatively small and positive.

Mercury and Venus may have formed with angular momenta different from the present values. It is considered by several authors that several factors (e.g., gravitational and atmospheric tides, core-mantle friction, and planetary perturbations) could change their angular momenta. Mercury rotates three times for every two revolutions around the Sun (the 3:2 spin–orbit resonance). Such resonance is considered to be caused by large variations in orbital eccentricity of Mercury. In our model, the angular momenta of the terrestrial planets could get their present values (exclusive for the Mercury's spin-orbit resonance) at the stage of formation of the planets. We suppose that for the terrestrial feeding zone, sizes of largest initial condensations could be maximum at a=1 AU, and the plot of sizes of largest condensations vs. a could have a minimum near the present orbit of Mercury. Such distribution of large condensations can explain the differences in the angular momenta of the terrestrial planets.

Conclusions

The embryos of the Earth and the Moon could form as a result of contraction of the same parental rarefied condensation. 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. The present angular momentum of the Earth-Moon system could be acquired at the collision of two identical uniform rarefied condensations with sizes of Hill spheres, which total mass was about 0.1 of the mass of the Earth and which heliocentric orbits were circular. As the angular momentum increased at the stage of growth of the embryos, the mass of the initial parental condensation could be even less than 0.02 of the Earth mass.

For the mass of the parental condensation not less than 0.2 of the Earth mass, the angular momentum of the condensation needed for formation of the embryos of the Earth-Moon system and equaled to the present angular momentum of the system could be acquired during accumulation of small objects by the condensation. However, in the case of the main contribution of small objects and initial spin to the final angular momentum of the parental condensation, Venus and Mars could also form with large satellites as the Earth, because in this case their parental condensations could also get large enough angular momentum. The absence of large satellites of the terrestrial planets other than the Earth can be caused by that their parental condensations did not collide with such large condensations as the Earth's parental condensation did.

Besides the main collision, which was followed by formation of the condensation that was a parent for the embryos of the Earth and the Moon, there could be another 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. Solid embryos of the Earth and the Moon could form as a result of contraction of the parental condensation.

Depending on eccentricities of the planetesimals that collided with the embryos, 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 a factor of ten.

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