# The Earth-Moon system as a typical binary in the Solar System

S. Ipatov[1,2]

[1]Vernadsky Institute of Geochemistry and Analytical Chemistry of Russian Academy of Sciences, Moscow, Russia
[2]Space Research Institute of Russian Academy of Sciences, Moscow, Russia

In recent years new arguments in favor of the formation of solid planetesimals by contraction of rarefied preplanetesimals (RPPs) have been found. It is often considered that masses of some RPPs can correspond to masses of solid bodies of diameter about 1000 km. [1] 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 0.1–0.6$M_E$ (where $M_E$ is the mass of the Earth). [2] and [3] supposed that transneptunian binaries were formed from RPPs. It was shown in [2] that the angular momenta acquired at collisions of RPPs moving in circular heliocentric orbits could have the same values as the angular momenta of discovered transneptunian and asteroid binaries. [4] obtained that the angular momenta used in [3] as initial data in calculations of the contraction of RPPs leading to formation of transneptunian binaries could be acquired at collisions of two RPPs moving in circular heliocentric orbits. I supposed that the fraction of RPPs collided with other RPPs during their contraction can be about the fraction of small bodies of diameter $d$ >100 km with satellites (among all such small bodies), i.e., it can be about 0.3 for objects formed in the transneptunian belt.

The model of collisions of RPPs explains negative angular momenta of some observed binaries, as about 20 percent of collisions of RPPs moving in circular heliocentric orbits lead to retrograde rotation. Note that if all RPPs got their angular momenta at their formation without mutual collisions, then the angular momenta of small bodies without satellites and those with satellites could be similar (but actually they differ considerably). Most of rarefied preasteroids could turn into solid asteroids before they collided with other preasteroids. Some present asteroids can be debris of larger solid bodies, and the formation of many binaries with primaries with $d$ <100 km can be explained by other models (not by contraction of RPPs).

[5] 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 which mass equaled to the mass of the Earth-Moon system. Using the formulas presented in [2], we obtained that the ratio $r_K$=$K_{EM}/K_{s2}$ of the angular momentum $K_{EM}$ of the Earth-Moon system to the angular momentum $K_{s2}$ at a typical collision of two identical RPPs - Hill spheres, which masses $m_2$ are equal to 0.5·1.0123$M_E$ and heliocentric orbits are circular, is about 0.0335. As $K_{s2} \propto (m_2)^{3/5}$ [2], then $K_{s2}$=$K_{EM}$ at $2m_2$=$0.0335^{3/5} \cdot 1.0123 M_E$=0.13$M_E$. For circular heliocentric orbits, the maximum value of $K_{s2}$ is greater by a factor of $0.6^{-1}$ than the above typical value. In this case, $r_K$=0.02 and $0.02^{3/5}$=0.096. Therefore, the angular momentum of the Earth-Moon system can be acquired at a collision of two RPPs with a total mass not smaller than the mass of Mars. We suppose that solid proto-Earth and proto-Moon (with masses $m_{Eo}$ and $m_{Mo}$) could be formed from a RPP (e.g., according to the models of contraction of a RPP [3,5]).

Let us consider the model of the growth of proto-Earth and proto-Moon to the present masses of the Earth and the Moon ($M_E$ and 0.0123$M_E$, 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 a radius of a considered object). Such proportionality can be considered for large enough eccentricities of planetesimals. In this case, $r_{Mo}$=$m_{Mo}/M_E$ = $[(0.0123)^{-2/3} - k + k \cdot (m_{Eo}/M_E)^{-2/3})]^{-3/2}$, where $k$=$(k_d)^{-2/3}$, and $k_d$ is the ratio of the density of the growing Moon to that of the growing Earth ($k_d$=0.6 for the present Earth and Moon). 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 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. If we consider that effective radii of the objects are proportional to $r^2$ (the case of relatively small relative velocities of planetesimals), then at $r_{Eo}$=0.1 for $k_d$ equal 1 and 0.6, we obtain $f_M$ equal to 0.04 and 0.05, respectively.

In the above model, the Moon could acquire up to 1/3 of its mass at the stage of accumulation of solid bodies, while the mass of the growing Earth increased by a factor of ten, but probably the initial mass of a solid proto-Earth exceeded 0.1$M_E$. Probably, the RPPs that contracted and formed the embryos of other terrestrial planets did not collide with massive RPPs, and therefore they did not get large enough angular momentum needed to form massive satellites.

**References:** [1] Lyra W., et al. (2008). A&A 491, L41–L44. [2] Ipatov S.I. (2010). Mon. Not. R. Astron. Soc. 403, 405–414. [3] Nesvorny D., Youdin A.N., Richardson D.C. (2010). Astron. J. 140, 785–793. [4] Ipatov S.I. (2013). Abstracts of 44th LPSC. 1488. [5] Galimov E.M., Krivtsov A.M. (2012). Origin of the Moon. New concept. / De Gruyter. Berlin. 168 p.