Astronomical and Astrophysical Transactions (*AApTr*), 2016, Vol. 29, Issue 4, pp. 539–546,
ISSN 1055-6796, Photocopying permitted by license only, ©Cambridge Scientific Publishers

Co-accretion statistical model of formation of the Earth–Moon system and the problem of the chemical composition of the presatellite swarm

G.V. Pechernikova*

Institute of Geosphere Dynamics, Russian Academy of Sciences, 38 Leninsky Pr., Building 1, Moscow, 119334, Russia

Received 15 September, 2015

The article gives a brief description of the generalized co-accretion statistical model of the Earth–Moon system formation. We discuss the basic mechanisms of replenishment of protosatellite swarm by substance, as well as the average composition of the growing Earth, largest planetesimals and protolunar disk.

Keywords: Protoplanetary disks – planets and satellites: formation – Earth–Moon

1 Introduction

Models of the Moon's origin can be divided into several areas. Here we will mention three. The first direction – co-accretion model – is the formation of near-Earth presatellite swarm during the growth of the Earth. For the first time this theory was offered by E.L. Ruskol (Ruskol, 1960, 1975), and later by American planetary scientists (Harris, Kaula, 1974). However, these models lead to the deficit of mass and angular momentum of prelunar swarm, although the co-accretion model describes well the satellite systems of giant planets.

The second trend, which arose as an alternative to the first one to explain the large mass ratio of the Moon and the Earth (1/81), and a large angular momentum of the Earth–Moon system – are different versions of the giant impact hypothesis (the collision of proto-Earth in the late stage of its growth with another planet, often called Theia) first proposed in (Hartmann, Davis, 1975; Cameron, Ward, 1976). In the megaimpact model almost tangential impact Theia formed a massive protolunar disc with a large angular momentum, from which the Moon subsequently formed. In these models the following input parameters are selected: the mass ratio of the impactor and the growing Earth, the composition of the impactor, impact velocity and impact parameter, so that the result is a system of the Earth–Moon at a predetermined ratio of the masses and angular momentum. With an appropriate choice of input

*Email: pechernikova@idg.chph.ras.ru

parameters almost everything can be explained. However, questions remain about the likelihood of such a "specially selected" impact and great difficulties with reference to geochemical character.

Recently, Phil. Trans. R. Soc. A published the results of the discussion of the origin of the Moon (Discussion Meeting Issue, 2014) with an introductory article (Stevenson, Halliday, 2014), which noted that in lunar science at the moment "there are two key sources of information for elucidating the origin of the Moon, the data which have become significantly more comprehensive in recent years. The first is new dynamic modelling, which is not just based on more powerful computational codes but also on a challenging exploration of the uncertainty surrounding some fundamental accretion parameters. The second is measurement of the isotopic composition of particular elements in lunar and terrestrial samples at unprecedented precision".

More than thirty authors of 18 works participated in the discussion of the theory of the origin of the Earth–Moon system. About a third of the work contains more complex scenarios of megaimpact up to "non-canonical" in an attempt to explain the advanced features of the Earth–Moon system. Most of the work is devoted to the differences in the chemical composition of the Moon and the Earth with almost complete coincidence of isotopic systems. According to Jay Meloche (2014) "Recent comparisons of the isotopic compositions of the Earth and the Moon show that, unlike nearly every other body known in the Solar System, our satellites isotopic ratios are nearly identical to the Earth's for nearly every isotopic system... This situation is not readily explained by current impact models of the Moon's origin".

Formation of the Earth–Moon system by solid accumulation was investigated earlier in the two extreme models:

Model I – co-accretion model: formation of a protolunar swarm by gravitational capture of bodies and particles into the sphere of Hill of growing planet, and

Model II – megaimpact model (the giant impact hypothesis): formation of a protolunar swarm as a result of ejection of matter at an oblique impact of a very large body.

Our model is an intermediate one:

Model III – co-accretion model plus macroimpacts: the formation of the near-Earth low-mass swarm through gravitational capture of bodies and particles from the feeding zone of the planet and capture by this swarm of material ejected by impacts of many large bodies in the process of growth of the Earth (Pechernikova, 1989; Vityazev, Pechernikova, 1996).

2 Co-accretion statistical model

More than once the similarity of planetary and satellite systems was noted. And just as the Sun was formed simultaneously with the protoplanetary disk, in the co-accretion model the growth of the planet is considered with simultaneous formation of a circumplanetary protosatellite swarm. Moreover, the distribution of mass and angular momentum in the Solar system and satellite systems, including the Earth–Moon system are similar – the bulk of the system is concentrated in the central body, while the moment – in the bodies in orbits.

Formation of near-planetary protosatellite swarms is treated as a process accompanying the growth of planets themselves (Safronov et al., 1986; Vityazev et al., 1990; Vityazev, Pechernikova, 1991). Early attempts to solve the problem of the prelunar swarm origin in a framework of the co-accretion hypothesis have not been successful. As it is shown in (Pechernikova et al., 1984; Vityazev et al., 1990; Vityazev, Pechernikova, 1991), the prelunar swarm mass in co-accretion scheme (Ruskol, 1975) does not exceed 10^{-4}–10^{-5} of a planet's mass. A failure of the model of Ruskol (1975) and increasing comprehension of important role of large bodies in the planet accumulation have drawn attention to the megaimpact hypothesis (Safronov et al., 1986; Origin of the Moon, 1986). The weak point in this approach lays in the fact that contribution of all but one largest body in the mass spectrum of preplanetary bodies should be considered negligible. Cosmochemical and geochemical consequences of both approaches remained undeveloped.

In (Pechernikova et al., 1984; Vityazev et al., 1990; Vityazev, Pechernikova, 1991) we developed a statistical model of formation of the prelunar swarm in the context of the standard scenario of the formation of the Solar system (Vityazev et al., 1990). This model is based on the theory of accretion of the mass $m(t)$ and angular momentum $K(t)$ by growing planets and allows for evolution of a mass distribution of planetesimals $n(m,t)$. The inclusion of macroimpacts responsible for the ejection of the small part (up to 10^{-1} in terms of mass of falling bodies) of matter from the surface of the growing planet into the ballistic and heliocentric orbits permits us to do away with drawbacks of the early approaches and to advance understanding of cosmochemical aspect of the problem.

We found it useful to reproduce here a fragment of the known picture "Evolution of the preplanetary disk", to which we added a growing Earth and a near-Earth protosatellite swarm. The most important stages for us are the main and terminal ($t \sim$ 10–100 m.y.) stages of planetary growth in the near-Sun zone (less than 3 AU), when the primary gas had already dissipated but solid components were present as numerous bodies with sizes r and masses m, ranging from particles of dust to protoplanets (Fig. 1).

The extension of the theory of accumulation of the mass and angular momentum to the case of a planet with the swarm (Pechernikova et al., 1984) makes possible the construction of the theory of circumplanetary disk evolution. In a flat swarm approximation (a model of relatively thin disk rotating with a Keplerian velocity about its symmetry axis passing through the planet), the surface density of matter $\sigma_2(R_2,t)$ satisfies the equation

$$\frac{\partial\sigma_2}{\partial t}+\frac{1}{R_2}\frac{\partial}{\partial R_2}\left(\sigma_2 R_2\sum_i v_{R_i}\right)=\sum_j I_j(\sigma_1,\sigma_2,R_2,t),$$

where subscripts 1 and 2 specify quantities related to the planetary zone and near-planetary swarm, respectively; R_2 is the distance in the swarm from the symmetry axis; v_{R_i} is the radial velocity of particle motion caused by i-th factor; and I_j is the inflow of matter captured by the swarm per unit time and caused by a j-th factor. The second term describes the dominant processes that redistribute material in the swarm, i.e., the radial diffusion and radial drift due to the deficiency in the angular momentum of captured matter and the growth of the planet itself, resulting in settling

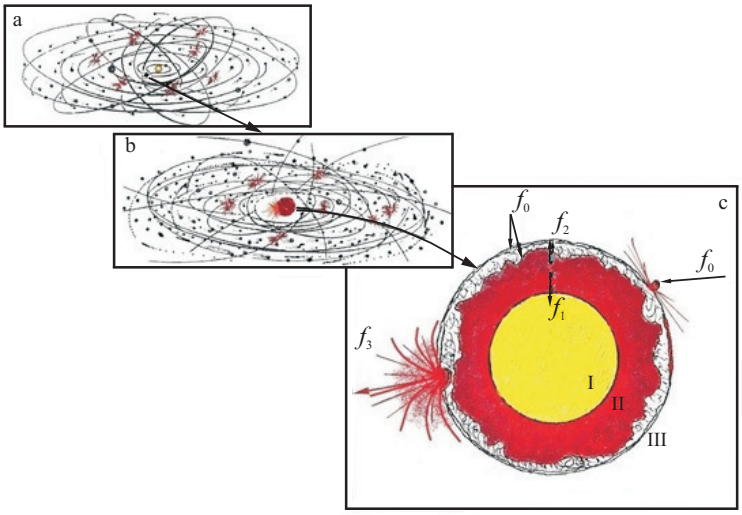


Figure 1 Main stage of planetary growth in the preplanetary disk. (a) Preplanetary disk, (b) growing Earth with near-Earth prelunar swarm, and (c) Earth. I, II and III denote primitive core, mantle, and crust, all forming during the Earth's growth and differentiation. Arrows indicate mass fluxes: f_0 from the planetary feeding zone into the crust and mantle; f_1, from the mantle into the core; f_2, from the mantle into the crust; and f_3, matter ejected onto ballistic and heliocentric orbits by impacts. The "instantaneous" lower boundary of the impact mixing layer is shown.

of matter from the internal swarm zone onto the planet. The main source of the swarm matter in the model (Ruskol, 1975) is the capture of preplanetary disk particles at their collisions.

In the work (Pechernikova, 1989) the formation of more massive presatellite swarms was considered in a more complex model, with involving additional mechanisms that enhance mass accumulation in the swarm. Apparently, the dominant mechanism is the ejection of particles into ballistic and heliocentric orbits by impacts of planetesimals on a growing planet, with the subsequent partial capture of the ejected matter into the protolunar swarm. A mass of the matter that is thrown out of the sphere of influence of the planet at such the impact may reach 10^{-1} of the projectile mass.

Our co-accretion statistical model of formation of Earth–Moon system is defined by three components:

A) The theory of the formation and evolution of near-Earth prelunar swarm (model I) considered the gravitational capture of bodies in the Hill's sphere of a growing planet at collisions of particles not related to the planet ("free-free" collisions), and gravitational capture of bodies at collisions of particles from the feeding zone of a planet with swarm particles ("free-bound" collisions). As already noted, this model allows us to describe the formation of satellite systems with a total mass of $\sim 10^{-4}$–10^{-5} of the planet's mass. This low-mass circumplanetary swarm will be regarded as "seed".

B) In the works (Svetsov, Pechernikova, 2012; Svetsov, 2013) as a result of the collision simulation of differentiated protoplanetary bodies with the growing planet it was obtained the dependence of the total mass of the impact ejection on heliocentric

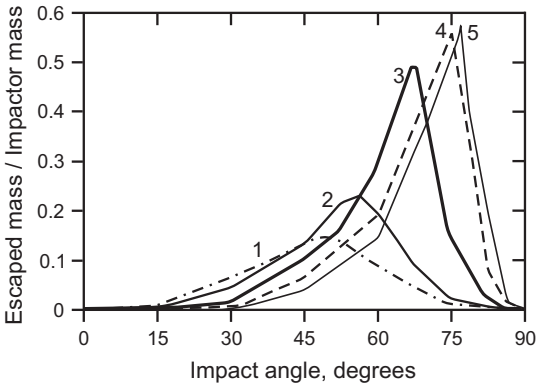


Figure 2 Relative total mass of particles escaped to heliocentric orbits as a function of impact angles for a few relative diameters of bodies. Ratio of impactor diameter to planet diameter δ: 1 – $\delta = 0.3$, 2 – $\delta = 0.2$, 3 – $\delta = 0.1$, 4 – $\delta = 0.05$, 5 – $\delta = 0.025$. The mass of the planet is 0.7 from the present mass of the Earth (Svetsov, Pechernikova, 2012).

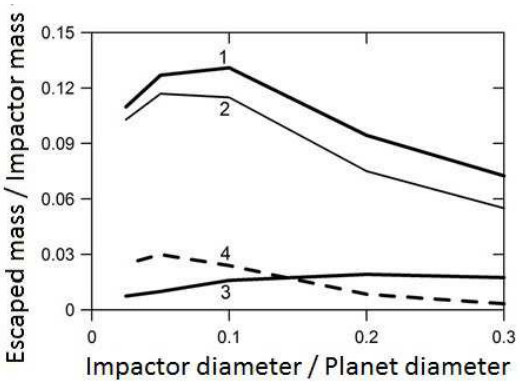


Figure 3 Averaged over impact angles relative mass of particles escaped to heliocentric orbits as a function of relative impactor diameter δ: 1 – total mass, 2 – mass of impactor particles, 3 – mass of target particles, 4 – mass of impactor core particles (Svetsov, Pechernikova, 2012).

orbit (and separately masses ejected material of the upper shells of the planet, the body-impactor and his core) on the direction of the impact velocity (Fig. 2) and on the ratio of the sizes of the colliding bodies (Fig. 3).

It was also shown that a particle mass, ejected to the heliocentric orbits at the macroimpacts, is more than three times the mass of the Moon, and the substance is of the same composition as the material from which the Earth formed, but is depleted in iron (Svetsov, 2013). The substance ejected from the planet by impacts substantially increases (by up to two orders of magnitude) the background density of matter in the planetary Hill's sphere. In (Vityazev, Pechernikova, 1996) it was shown that the mass accumulated in the swarm is proportional to σ_1, i.e. the gravitational capture of bodies in the swarm in free-free and free-bound collisions increases.

C) There are very encouraging estimates of a swarm taking into account material ejected in collisions of large objects with the planet onto ballistic and heliocentric orbits, when it interacts with particles in near-Earth orbits (Gorkavyi, 2007). We call this type of capture of substance in swarm, by analogy with the previous two, a capture at "ejection-bound" collisions. It is the third source of replenishment of the swarm.

3 Composition of planetesimals

In the works (Pechernikova et al., 2003; Pechernikova et al., 2014) the authors showed that during the growth of the Earth between 0.5 and 0.99 of its current mass, more than 50% of the material of the largest planetesimals (in the top ten of the power mass distribution) were brought on the Earth – here is so great role of large bodies in the Earth formation.

Analytical estimations of the axial rotation of the planets acquired during their growth, taking into account the large bodies in the framework of the standard scenario of the origin of the Solar system, and estimations received in the simulation of the Earth growth in the stochastic model are consistent with (and even rather confirm) the possibility of forming of a protolunar swarm with an appropriate orbital moment (Pechernikova, 2013).

In the work (Pechernikova, 2014) the evolution of matter in the feeding zone of the growing planet is discussed, taking into account the influence of large bodies, in order to assess the degree of homogeneity in the composition of planetesimals, from which the substance of the Earth–Moon system is formed (in the framework of the co-accretion model).

The feeding zone of the growing Earth is quite narrow – only about a half of the astronomical unit, there is no sharp temperature limit, this implies a relatively uniform composition of solids. Moreover:

1. The rapid growth of the width of the feeding zone leads to good mixing of planetesimals within the zone.

2. The growth of the planet occurs mainly due to collisions with large bodies, in which the substance is also well mixed, and during the mass accumulation in elliptical orbits in different parts of the feeding zone, and with the shock stirring in collisions with smaller bodies (Vityazev, Pechernikova, 1996), resulting in homogenisation of the planet's composition.

3. With the destruction of protoplanetary bodies as a result of high-speed collisions, (Vityazev et al., 1990) scatter of fragments and then their re-accumulation by other bodies occur – it is additional mixing.

4. As shown in (Kleine et al., 2009) the strong fractionation of lithophile Hf from siderophile W during core formation makes the Hf–W system an ideal chronometer for this major differentiation event. However, for larger planets the calculated Hf-W ages are particularly sensitive to the occurrence of large impacts. Therefore, tungsten model ages for core formation in Earth are determined with a wide range of uncertainty. At the same time, calculated core formation ages for Mars (Kleine et al., 2009) are in the range from 0 to 20 Myr after CAI formation. It can be assumed that Mars, the mass of which is about 0.1 of the mass of the Earth has not grown

to the destructive macroimpacts. This, in turn, allows the same early differentiation and core formation in the growing Earth and the largest planetesimals with similar composition, respectively.

Acknowledgements

I thank Andrey Vityazev, Victor Sergeev and Vladimir Svetsov for their interest and help in the work.

References

Cameron A.G.W., Ward W.R. (1976) LPSC 7, 120.
Discussion Meeting Issue (2014), "Origin of the Moon: challenges and prospects". http://rsta.royalsocietypublishing.org/content/372/2024
Gorkavyi N.N. (2007), Izv. Krymsk. Astrofiz. Observ., 103(2), 143.
Harris A.W., Kaula W.M. (1974) Colloq. IAU 28 "Planetary Satellites", Ithaca.
Hartmann W.K., Davis D.R. (1975), Icarus 24, 504.
Kleine T., Touboul M., Bourdon B., et al. (2009) GCA 73, 5150.
Melosh H. J. (2014) Phil. Trans. R. Soc. 372, 2024 Origin of the Moon (1986), eds. W.K. Hartmann, R.J. Phillips, G.J. Taylor. Houston: Lunar and Planetary Inst.
Pechernikova G.V. (1989) in: Planetary cosmogony and Earth sciences, ed. W.A. Magnizki, Moscow: Nauka, 106.
Pechernikova G.V. (2013) in: Collection of scientific papers IGD RAS (4). Moscow: GEOS, 61.
Pechernikova G.V. (2014) in: Collection of scientific papers IGD RAS (6). Moscow: GEOS, 154.
Pechernikova G.V., Davidenko I.W., Vityazev A.V. (2003). III Internat. Conf. On Large Meteorite Impacts. Nordlingen, #4015.
Pechernikova G.V., Majeva S.V., Vityazev A.V. (1984) SvAL, 9, 703.
Pechernikova G.V., Svetsov V.V., Sergeev V.N. (2014) Abstracts of conference on the Program 28 of the Presidium of RAS "Problems of biosphere origin and evolution", 27.
Ruskol E. L. (1960) SvA 4, 657 (AZh 37, 690).
Ruskol E.L. (1975) The Origin of the Moon, Moscow: Nauka (Trans. NASA TT-F-16623).
Safronov V.S., Pechernikova G.V., Ruskol E.L., Vityazev A.V. (1986) in: Satellites / Eds. J.A. Burns, M.S. Matthews. Tucson: The University of Arizona Press, 89.
Stevenson D.J., Halliday A.N. (2014) Phil. Trans. R. Soc. A, 2014 372, 20140289.
Svetsov V.V. (2013) in: Collection of scientific papers IGD RAS (4). Moscow: GEOS, 66.
Svetsov V.V., Pechernikova G.V. (2012) ESLAB Symposium on Formation and Evolution of Moons, Noordwijk, The Netherlands.
Vityazev A.V., Pechernikova G.V. (1991) in: Planetary Sciences, American and Soviet Research, eds. T.M. Donahue and K.K. Trivers, Washington, DC: National Academy Press, 143.

Vityazev A.V., Pechernikova G.V. (1996) Izvestiya, Physics of the Solid Earth, 32, 471 (Fizika Zemli, 6, 3).

Vityazev A.V., Pechernikova G.V., Safronov, V.S. (1990) Planety zemnoi gruppy: Proiskhozhdenie i rannyaya evolyutsiya. (Terrestrial Planets: Origin and Early Evolution). Moscow: Nauka (in Russian).

©2016 Astronomical and Astrophysical Transactions (AApTr), Vol. 29, Issue 4