A MODEL OF MOON FORMATION FROM EJECTA OF MACROIMPACTS ON THE EARTH.

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Introduction: The problem of Moon origin can briefly be stated as follows: how and when has a fairly massive satellite ($m_{\text{Moon}}/m_{\text{Earth}} = 1/81$) with a mean density of 3.34 g/cm^3 and a composition appreciably different from that of the Earth been formed near the Earth, whose mean density is about 4.05 ± 0.05 g/cm^3 (reduced to a pressure of 10 kbar) and whose composition is close to the average composition of chondrites? Unlike the Earth, to a first approximation the Moon has no metallic iron, its oxidized iron content is approximately 1.5–2 times higher than the Earth's mantle averaged value, and its refractory content (Al_2O_3 and CaO abundances) is also greater than the mantle averages.

As distinct from the most popular hypothesis of Moon origin after a single impact of a roughly Mars-sized body [1] (megaimpact), we suggest a statistical model including the evolution of a population of large planetesimals which is gradually exhausted as a result of catastrophic encounters with growing planets (macroimpacts). We consider formation of a prelunar near-Earth swarm of small bodies from which the Moon later accreted within the framework of the coaccretion theory [2]. But this theory meets difficulties with accumulation of an adequate mass in the protolunar disk and with explanation of the compositional differences. We assume that the swarm mass increases due to capture of material ejected from the upper shell of a growing planet after numerous impacts of large planetesimals [3]. In this paper we address the mechanical side of the problem of formation of a planet with a large satellite. If it turns out that the swarm acquires sufficient mass, a more complex compositional problem related to differentiation of growing bodies and mass transfer between them can be considered.

The model of protolunar swarm growth: The most important stages of evolution of the protoplanetary disk for our model are the main and terminal ($t \sim 10 - 100$ Myr) stages of planetary growth in the near-Sun zone (less than 3 AU) when the gas of a protoplanetary disk has already dissipated but solid components were present in the form of numerous bodies with various sizes and masses ranging from small particles of dust to protoplanets. The formation of near-planetary presatellite swarms is treated as a process accompanying the growth of the planet. In a flat swarm approximation (a model of relatively thin disk rotating with a Keplerian velocity about its symmetry axis passing through the planet center), the surface density of material $\sigma_2(R_2, t)$ satisfies the equation [4]

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

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; U_{Ri} is the radial velocity of particle motion caused by ith factor; and I_j is the inflow of material captured by the swarm per unit time and caused by a jth factor. The second term in this equation describes the dominant processes that redistribute material in the swarm, i.e., the radial diffusion and radial drift due to deficiency in the angular momentum of captured material, and the growth of the planet, involving deposition of material from the internal zone of the swarm onto the planet.

The model of presatellite swarm formation includes the equation of planetary growth, the equation of the surface density in the planetary feeding zone, the mass and velocity spectra of planetesimals, the equation for the angular momentum, and other relations [3], [4], [5], [6]. The main source of prelunar swarm material in the Schmidt–Ruskol–Safronov model [4] is the capture of preplanetary disk particles during their "free-free" and "free-bound" encounters. The equation adequately describes formation of low-density presatellite swarms typical for the giant planets. However, this approach predicts the formation of satellite systems whose total mass is only about 10^{-4}–10^{-5} of the mass of the planet m_p. For the formation of massive (10^{-1}–10^{-2} m_p) satellites we suggest a more complex model involving additional mechanisms that enhance mass accumulation in the swarm. Apparently, the dominant mechanism is ejection of particles into geocentric and heliocentric orbits by the impacts of planetesimals on the growing planet with subsequent partial capture of ejected material by the prelunar swarm. We used numerical simulations of impacts to estimate if the ejecta mass is sufficient for the formation of a massive satellite.

Numerical code for simulations of macroimpacts: Velocity distribution and escaped masses of projectile and target material after impacts of stony projectiles have been calculated in [7] for flat targets. Since the Earth sphericity is important for macroimpacts we have developed a 3D hydrodynamic code in which the hydrodynamic equations are solved in a spherical system of coordinates. An analogous 2D code has been used earlier for the simulations of head-on macroimpacts [8]. We modeled the impacts in which impactors consist of dunite and have diameters of 3000 km. The Earth is assumed to be in a modern state with a crust (granite), mantle (dunite) and iron core. The gravity field was taken as central and constant. The impact angles varied from 0 to 90° and impact velocities from 12 to 20 km/s. The numerical simulations give the mass and velocity distribution of ejecta and trajectories of ejecta particles.

Preliminary results of simulations: The computational results show that only a negligibly small mass (in comparison to the impactor) can be ejected to geocentric orbits in all the cases. However, some appreciable mass of ejecta can reach high altitudes and then either fall on the Earth or go to heliocentric orbits. This ejecta potentially can be captured by the prelunar swarm. At small impact angles (head-on or vertical impacts) the mass of this ejecta is also small, but this mass grows with impact angles. Masses of ejecta which passes on heliocentric orbits are shown in Fig. 1. For large impact angles (grazing impacts) a major part of impactor mass can continue the motion along its trajectory with high velocity, being heavily fragmented or pulverized. E.g., during the impact at 20 km/s and 60° the shock wave which propagates throgh the impactor has the maximum pressure about 100 GPa. When the impactor continues its motion after the impact, relative velocities of fragments reach several kilometers per second. The escaped projectile mass exceeds 80% of the initial projectile mass in this case.

The simulations show that, on the average, the relative mass of escaped material is substantially larger than $m_{\mathrm{Moon}}/m_{\mathrm{Earth}}$. This material can be captured by the prelunar swarm when the ejecta flies through the swarm or when the ejecta particles return to the Earth again during their motion along heliocentric orbits which pass near the Earth's orbit. The result depends on mass and velocity distributions of impactors, on the sizes of ejecta particles, on the efficiency of capture, swarm configuration and stability. These factors should be estimated in the future. Large impactors carry the bulk of the mass accreted by the planet. The impacts of large planetesimals on the Earth replenish the population of small bodies which have a greater probability to approach the Earth rather than be accreted by planetesimals. The impacts with low velocities produce smaller masses of escaped ejecta. However this ejecta has smaller velocities, moves closer to the Earth's orbit and has better chances to be captured by the prelunar swarm during its motion around the Sun.

Some conclusions: The masses which escape the Earth gravity after macroimpcts at 12–20 km/s are sufficient for formation of a Moon-sized satellite. On average, material of impactors prevails in high velocity ejecta. For completeness of the model it is necessary to estimate size distribution of ejecta and develop a physical and numerical model of interaction of ejecta material with the prelunar swarm of particles. The simulations of macroimpacts should also include earlier stages of Earth growth when it had smaller masses and smaller escape velocities.

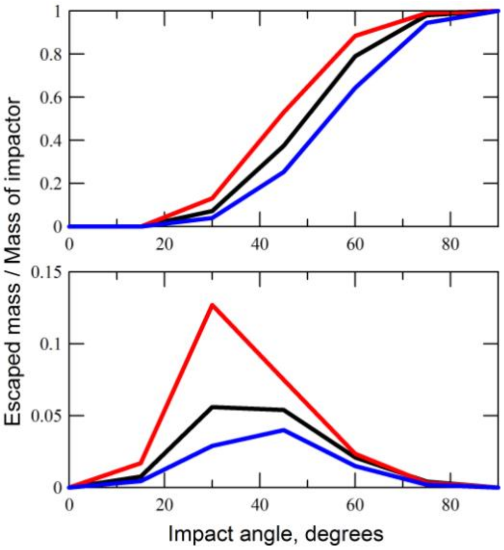

Fig. 1. Relative escaped masses of projectile (upper panel) and target (lower panel) after impacts of 3000-km-diameter asteroids on the Earth with impact velocities 12 km/s (blue), 15 km/s (black), and 20 km/s (red) as functions of impact angles. The impact angle is defined as an angle between the projectile velocity and the line connecting the centers of the Earth and projectile when the projectile comes to contact with the planetary surface.

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