MIGRATION OF CELESTIAL BODIES IN THE SOLAR SYSTEM

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We investigated several cases of migration of celestial bodies in the forming and present Solar System. The results of numerical integration of the equations of motion for the plane three-body problem (the Sun and two bodies) showed [6] that for initially circular heliocentric orbits and the chaotic variations in orbital elements at $\mu_1 \leq 10^{-5}$ the maximum eccentricity e_{max} usually doesn't exceed $7 - 8 \times \mu_1^{1/3}$, where μ_1 is a ratio of the larger body mass to the Sun mass. For initially eccentric orbits and a large time interval, the values of e_{max} may depend mostly on initial orbits but not on μ_1. We showed [1] that in the case of close encounters, using the spheres' method (two two-bodies problems) and choosing the radius of the sphere in an appropriate way, we can obtain almost the same values of e_{max} as those obtained by numerical integration. For the case of three identical bodies circling the Sun, the maximum eccentricity can be several tens of times larger than that for two such bodies [7]. The obtained results showed that some bodies of the beyond-Neptune belt can migrate to the orbit of Neptune under the gravitational influence of other bodies of this belt.

Our investigations of migration of bodies during the accumulation of planets were based mainly on the results of computer simulation of the evolution of disks that originally consisted of hundreds of gravitating bodies moving around the Sun [2, 5]. In some models the initial disks included also almost-formed planets. The mutual gravitational influence of bodies was taken into account by the spheres' method. We also analytically studied the dependencies of the time of disk evolution and the average eccentricity as a function of the number of bodies constituting the disk [3, 7]. The obtained results showed that each terrestrial planet incorporated planetesimals from the feeding zones of all these planets. The total mass of bodies ejected from the zones of giant planets into hyperbolic orbits may have been ten times as large as the mass of bodies that entered into the planets. The embryos of unformed planets with masses equal to several Earth masses in the zone of Jupiter and Saturn would be necessary to explain present eccentricities as well as present axial rotations of these planets. The embryos of Uranus and Neptune with initial masses equal to several Earth masses may have originated near the orbit of Saturn and then may have migrated to the present distances from the Sun moving all time in nearly circular orbits. The mass of solid bodies, which entered into Jupiter's envelope and nucleus, may be larger than that in any other planet and may exceed the Earth's mass by several tens' times. A large amount of water could be delivered to Earth during the accumulation of Uranus and Neptune.

We investigated the present migration of bodies to the Earth from the asteroid and trans-Neptune belts [8]. Computer simulations of the evolution of disks that originally consisted of planets and hundreds of bodies located in various regions of the Solar System were carried out. We obtained that some bodies,

which migrated to the Earth from these regions, replenished the family of bodies, which orbits entirely lie inside the Earth's orbit (and some orbits lie inside the orbit of Venus). Most of asteroids of the Amor group should have come from the asteroid belt. Together with the 3:1 gap, the 5:2 Kirkwood gap may play noticeable role in the replenishment of Apollo and Amor groups [4]. For most of bodies that collided the Earth, the time interval between the moment when they obtained the orbit intersecting the Earth's orbit and a collision with the Earth does not exceed 10 Myr.

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