Formation and Migration of Trans-Neptunian Objects

Sergei Ipatov[1,2]
(Email: siipatov@hotmail.com)
[1]Department of Physics and Astronomy, George Mason University, Fairfax, Virginia, USA
[2]Institute of Applied Mathematics, Moscow, Russia

In our opinion [a], some trans-Neptunian objects (TNOs) with diameter $d > 100$ km (and even Pluto and Charon) moving now in not very eccentric ($e < 0.3$) orbits could be formed directly by the compression of large rarefied dust condensations (with $a > 30$ AU), but not by the accretion of smaller solid planetesimals. We also suppose that some planetesimals with $d \sim 100$–1000 km in the feeding zone of the giant planets and with $d \sim 100$ km in the terrestrial planets' zone and some large main-belt asteroids could also be formed directly by such compression. Some smaller objects (TNOs, planetesimals, asteroids) could be debris of larger objects, and other such objects could be formed directly by compression of condensations. As in the case of accumulation of planetesimals, there could be a "run-away" accretion of condensations and there was a distribution in masses of final condensations, which compressed into planetesimals. Based on our runs of formation of the giant planets, in 1987 we supposed [b] that there were two groups of TNOs and, besides TNOs formed beyond 30 AU and moving in low eccentric orbits, there were former planetesimals from the zone of the giant planets in highly eccentric orbits beyond Neptune. Migration of almost formed Uranus and Neptune from the zone near Saturn's orbit to their present orbit was studied by us 13 years ago [c,d,e]. Collisional evolution of TNOs was discussed in [f]. It is usually considered that TNO binaries can be produced due to the gravitational interactions or collisions of future binaries with an object (or objects) that entered their Hill sphere. In our opinion [g], binary TNOs (including Pluto-Charon) were formed at that time when orbits of TNOs were almost circular, as for such orbits, two TNOs entering inside their Hill sphere could move there for a long time. We suppose that a considerable portion of TNO binaries could be formed at the stage of compression of condensations. At this stage, the diameters of condensations, and so probabilities of their mutual collisions and probabilities of formation of binaries were much greater than those for solid TNOs. The stage of condensations was longer for TNOs than that for asteroids, and therefore binary asteroids (which could be mainly formed after the formation of solid objects) are less frequent and more differ in mass than binary TNOs. Besides, at the initial stage of solar system formation, eccentricities of asteroids could be mainly greater (due to the influence of the forming Jupiter and planetesimals from its feeding zone) than those of TNOs. As migration of TNOs to Jupiter's orbit was investigated by several authors, we integrated the orbital evolution of Jupiter-crossing objects (several papers on this problem are presented in astro-ph). Analysis of these runs shows that the total amount of water delivered to the Earth during the formation of the giant planets was about the mass of water in Earth oceans. The ratio of the total mass of water delivered to a planet to the mass of the planet was greater for Mars than for Earth. The end of the bombardment of terrestrial planets could be caused mainly by the planetesimals that had got highly eccentric orbits located mainly beyond Neptune.

Acknowledgment. This work was supported by NASA grant NAG5-10776 and INTAS (00-240).

[a] Ipatov, S.I., Formation of Trans-Neptunian Objects, *Lunar Planet. Sci. Conf. XXXII Abstracts*, #1165, 2001.

[b] Ipatov, S.I., Accumulation and Migration of the Bodies from the Zones of Giant Planets, *Earth, Moon, and Planets*, **39**, 101–128, 1987.

[c] Ipatov, S.I., Evolution of Initially Highly Eccentric Orbits of the Growing Nuclei of the Giant Planets, Sov. Astron. Lett., **17**, 113–119, 1991.

[d] Ipatov, S.I., Possible Migration of the Giant Planets' Embryos, *Lunar Planet. Sci. Conf. XXII Abstracts*, 607–608, 1991.

[e] Ipatov, S.I., Migration of Bodies in the Accretion of Planets, *Solar Syst. Res.*, **27**, 65–79, 1993.

[f] Ipatov, S.I., Migration of Small Bodies to the Earth, *Solar Syst. Res.*, **29**, 261–286, 1995

[g] Ipatov, S.I., Formation and Migration of Trans-Neptunian Objects, *Proc. of the 14th Annual Astrophysics Conference in Maryland, "The Search for Other Worlds", submitted* (see astro-ph/0401279), 2004.