FORMATION OF TRANS-NEPTUNIAN OBJECTS.

S. I. Ipatov, University of Maryland, College Park, MD University of Maryland, College Park, MD 20740-2403, USA, siipatov@mail333.com.

Formation of Edgeworth-Kuiper belt objects: In most models of the formation and collisional evolution of the Edgeworth-Kuiper belt (EKB) (e.g., [1-7]), the process of accumulation of trans-Neptunian objects (TNOs) took place at small (~0.001) eccentricities and a massive belt. In our opinion, it is probable that, due to the gravitational influence of the forming giant planets, TNOs, and migrating planetesimals, small eccentricities of TNOs could not exist during all the time needed for the accumulation of TNOs with diameter d>100 km. More references on the problems discussed in our abstracts can be found in our papers and in [8].

We consider [9] that TNOs with $d \geq 100$ km moving now in not very eccentric 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. The role of turbulence could decrease with an increase of distance from the Sun, so, probably, condensations could be formed at least beyond Saturn's orbit.

Probably, some planetesimals with d~100-1000 km in the feeding zone of the giant planets and even large main-belt asteroids also could be formed directly by the compression of rarefied dust condensations. Some smaller objects (TNOs, planetesimals, asteroids) could be debris of larger objects, and other such objects could be formed directly by compression of condensations. Even if at some instants of time at approximately the same distance from the Sun, the dimensions of initial condensations, which had been formed from the dust layer due to gravitational instability, had been almost identical, there was a distribution in masses of final condensations, which compressed into the planetesimals. As in the case of accumulation of planetesimals, there could be a “run-away” accretion of condensations. It may be possible that, during the time needed for compression of condensations into planetesimals, some largest final condensations could reach such masses that they formed planetesimals with diameter equal to several hundreds kilometers.

Formation of scattered disk objects (SDOs): Five years before the first TNO was discovered in 1992, based on our runs of the formation of the giant planets we supposed [10] 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. During accumulation of the giant planets, planetesimals with a total mass equal to several tens $m_\oplus$ could enter from the feeding zone of the giant planets into the trans-Neptunian region, increased eccentricities and inclinations of 'local' TNOs, which initial mass could exceed $10m_\oplus$, and swept most of them. A very small fraction of such planetesimals could left in eccentrical orbits beyond Neptune and became so called "scattered disk objects" (SDOs). Later on similar model of the formation of SDOs were considered by several authors in more detail [e.g., 11-12]. The end of the bombardment of terrestrial planets could be caused mainly by the planetesimals that had got highly eccentric and inclined orbits located mainly beyond Neptune.

The total mass of planetesimals in the feeding zones of the giant planets, probably, didn’t exceed $300m_\oplus$, and only a smaller part of them could get into the Oort and Hills clouds and into the region between 50 and 1000 AU. So it seems more probable that the total mass of the objects located beyond Neptune’s orbit doesn’t exceed several tens $m_\oplus$.

The total mass of planetesimals in the feeding zone of Uranus and Neptune could exceed $100m_\oplus$. Most of these planetesimals could still move in this zone when Jupiter and Saturn had accreted the bulk of their masses. Our computer runs [13-15] showed that the embryos of Uranus and Neptune could increase their semimajor axes from ≤10 AU to their present values, moving permanently in orbits with small eccentricities, due to gravitational interactions with the planetesimals that migrated from beyond 10 AU to Jupiter, which ejected most of them into hyperbolic orbits. Later on, similar results were obtained by Thommes *et al*. [16-17] by numerical integrations using much faster computers. In our old runs the mutual gravitational influence was taken into account by the method of spheres. In contrast to Opik's scheme, in our algorithm the probability of an encounter of two bodies depends also on the synodic period of the bodies [18-19]. An effective method for choosing the pairs of encountering bodies was worked out [19-20]. The comparison of our old results with those obtained by Thommes *et al*. [16-17] shows that the method of spheres can provide statistically reliable results for many bodies moving in eccentric orbits. Our results on the evolution of disks of gravitating bodies coagulating under collisions in the feeding zone of the terrestrial planets, which we obtained by the method of spheres (e.g., [15, 21-22]) are also close to the results obtained by numerical integration (e.g., [23-24]). Ipatov [25] studied collisional evolution of TNOs.

Formation of binaries: It is 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. Different models of the formation of TNO binaries are presented e.g. in [26-29]. In our opinion, binary TNOs (including Pluto-Charon) were probably formed at that time when heliocentric orbits of TNOs were almost circular. For such orbits, two TNOs entering inside their Hill sphere could move there for a long time (e.g., greater than half an orbital period [10]). We suppose [30-31] that a considerable fraction of TNO binaries could be formed at the stage of compression of dust condensations. At this stage, the diameters of condensations, and so the probabilities of their mutual collisions and the 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.

Total mass of water delivered to the Earth during giant planets formation: The total mass of water delivered to the Earth during formation of the giant planets is $M_w=M_J P_{JE} k_i$, where M_J is the total mass of planetesimals from the feeding zones of these planets that got Jupiter-crossing orbits during evolution, $\boldsymbol{P_{JE}}$ is a probability P of a collision of a Jupiter-crossing object (JCO) with the Earth during its lifetime, and $\boldsymbol{k_i}$ is the fraction of water ices in planetesimals. For $M_J=100m_\oplus$ (where $m_\oplus$ is the mass of the Earth), $k_i=0.5$, and $P_{JE}=4\cdot10^{-6}$ (in our runs of the orbital evolution of 30,000 JCOs [32-35] we got even larger mean values of P_{JE}) we have $M_w=2\cdot10^{-4}\cdot m_\oplus$. This value is about the mass of the Earth oceans, and the amount of water delivered to the Earth during the process of the giant planets formation could exceed the mass of the Earth oceans (such conclusions were also made by us in [25, 36]). Comparison of our estimates with results of other scientists is discussed in [35]. The mass of water delivered to Venus can be of the same order of magnitude than that for Earth. The fraction of the mass of the planet delivered from beyond Jupiter's orbit can be greater for Mars than for Earth. So there could be relatively large ancient oceans on Mars and Venus.

As migration of TNOs to Jupiter's orbit was studied by several authors [37-38], we considered [32-35] migration of objects from Jupiter's orbit to the terrestrial planets.

References: **[1]** Davis D. R. and Farinella P. (1997) *Icarus*, 125, 50-60. **[2]** Durda D. D. and Stern S. A. (2000) *Icarus*, 145, 220-229. **[3]** Kenyon S. J. and Luu J. X. (1998) *Astron. J.*, 115, 2136-2160. **[4]** Kenyon S. J. and Luu J. X. (1999) *Astron. J.*, 118, 1101-1119. **[5]** Stern S. A. (1995) *Astron. J.*, 110, 856-868. **[6]** Stern S. A. (1996) *Astron. Astrophys.*, 310, 999-1010. **[7]** Stern S. A. and Colwell J. E. (1997) *Astron. J.*, 114, 841-849. **[8]** Ipatov, S.I., http://planetquest1.jpl.nasa.gov/TPFDarwinConf/confProceedings.cfm, poster 045 (2004). **[9]** Ipatov S.I., (2001) *LPSC*, print-only abstracts (#1165). **[10]** Ipatov S. I. (1987) *Earth, Moon, and Planets*, 39, 101-128. **[11]** Gomes R.S. (2003) *Icarus*, 161, 404-418. **[12]** Morbidelli, A. and Levison H.F. (2003) *Nature*, 422, 30-31. **[13]** Ipatov S.I. (1991) *Sov. Astron. Letters*, 17, 113-119. **[14]** Ipatov S.I. (1991) *LPSC*, 607-608. **[15]** Ipatov S. I. (1993) *Solar Syst. Res.*, 27, 65-79. **[16]** Thommes E.W., Duncan M.J., and Levison H.F. (1999) *Nature*, 402, 635-638. **[17]** Thommes E.W., Duncan M.J., and Levison H.F. (2002) *Astron. J*, 123, 2862-2883. **[18]** Ipatov S.I. (1988) *Soviet Astronomy*, 32 (65), N 5, 560-566. **[19]** Ipatov S. I. (2000) *Migration of Celestial Bodies in the Solar System*, Moscow, Editorial URSS, 320 pp. (in Russian). **[20]** Ipatov S.I. (1992) *Proc. Intern. IMACS Conference on Mathematical modelling and applied mathematics* (June 18-23, 1990, Moscow). Ed. by A.A.Samarskii and M.P. Sapagovas. Elsevier. Amsterdam, 245-252. **[21]** Ipatov S.I. (1981) *Sov. Astron.*, 25, 617-623. **[22]** Ipatov S.I. (1987) *Solar System Res.*, 21, N 3, 129-135. **[23]** Chambers J.E. (2001) *Icarus*, 152, 205-224. **[24]** Chambers J.E. and Wetherill G.W. (1998) *Icarus*, 136, 304-327. **[25]** Ipatov S.I. (1995) *Solar Syst. Res.*, 29, 261-286. **[26]** Weidenschilling S.J. (2002) *Icarus*, 160, 212-215. **[27]** Goldreich P., Lithwick Y., Sarl R. (2002) *Nature*, 402, 643-646. **[28]** Funato Y., Makino J., Hut P., Kokubo E., Kinoshita D. (2004) *http://arXiv.org/format/astro-ph/0402238*. **[29]** Petit J.-M. and Mousis O. (2004) *Icarus*, 168, 409-419. **[30]** Ipatov S.I. (2003) *BAAS*, 35, N 5, #15.06. **[31]** Ipatov S.I. (2004) *Proc. of the 14th Annual Astroph. Conf. in Maryland "The Search for Other Worlds"*, ed. by S.S. Holt and D. Deming, American Inst. of Physics, 277-280. **[32]** Ipatov S.I. (2002) *Asteroids, Comets, Meteors, 2002*, 371-374. **[33]** Ipatov S.I. and Mather J.C. (2003) *Earth, Moon, and Planets*, 92, 89-98. **[34]** Ipatov S.I. and Mather J.C. (2004) *Adv. Space Res.*, 33, 1524-1533. **[35]** Ipatov S.I. and Mather J.C. (2004) *Annals of the New York Acad. of Sciences*, 1017, 46-65. **[36]** Ipatov S.I. (2001) *Adv. Space Res.*, 28, 1107-1116. **[37]** Duncan M.J., Levison H.F., and Budd S.M. (1995) *Astron. J.*, 110, 3073-3081. **[38]** Levison H.F. and Duncan M.J. (1997) *Icarus*, 127, 13-23.