FORMATION OF TRANS-NEPTUNIAN OBJECTS. S.I. Ipatov, Institute of Applied Mathematics, Miusskaya sq. 4, Moscow 125047, Russia; ipatov@spp.keldysh.ru

Introduction: It was considered by many authors [1-3] that a dust disk around the forming Sun became thinner until its density reached a critical value about equal to the Roche density. At this density, the disk became unstable to perturbations by its own self-gravity and developed dust condensations. These initial condensations coagulated under collisions and formed larger condensations [1], which compressed and formed solid planetesimals. In [2] it was considered that initial dimensions of planetesimals in the zone of Neptune were about 100 km, and in the terrestrial feeding zone they were about 1 km. Greenberg et al. [4] supposed that initial dimensions of planetesimals from the Neptune's feeding zone were much smaller and were about 1 km. According to [5], the mass of the largest condensation in the region of Neptune could exceed 2m$_{\oplus}$, where m$_{\oplus}$ is the mass of the Earth. Some scientists consider [6] that turbulence prevented to gravitational instability and planetesimals probably were formed by coagulation of grain aggregates that collided due to differential settling, turbulence, and drag-induced orbital decay.

Formation and collisional evolution of the Edgeworth-Kuiper belt (EKB) was investigated in [7-14]. In these models, the process of accumulation of Edgeworth-Kuiper belt objects (EKBOs) took place at small (~0.001) eccentricities and a massive belt.

Formation of Edgeworth-Kuiber belt objects: Our runs showed [15-16] that maximal eccentricities of EKBOs always exceed 0.05 during 20 Myr under the gravitational influence of the giant planets. Gas drag could decrease eccentricities of planetesimals, and the gravitational influence of the forming giant planets could be less than that of the present planets. Nevertheless, to our opinion, it is probable that, due to the gravitational influence of the forming giant planets and migrating planetesimals, small eccentricities of EKBOs could not exist during all the time needed for accumulation of EKBOs with diameter d>100 km.

Eneev [17] supposed that large trans-Neptunian objects (TNOs) and all planets were formed by compression of large rarefied dust-gas condensations. We do not think that planets could be formed in such a way, but we consider that TNOs with d≥100 km moving now in not very eccentric orbits (i.e., EKBOs) 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 the orbit of Saturn.

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 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 objects: 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 [18-19] (excitation of TNOs was also considered in [20]). A small fraction of such planetesimals could left in eccentrical orbits beyond Neptune and became so called "scattered objects". 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 [19, 21] 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, the idea of a narrow zone, where all giant planets have been formed, was supported and further developed by Thommes et al. [22]. The total mass of planetesimals from the feeding zones of the giant planets that collided the Earth 4.5 to 4 Gyr ago was of the order of the mass of the water in the Earth's oceans [23-24]. The end of such bombardment could be caused mainly by the planetesimals which became scattered objects, because dynamical lifetimes of planetesimals located inside Neptune's orbit usually were less than 0.1 Gyr.

Collisional evolution of trans-Neptunian objects: Our estimates [16, 23] of the frequency of collisions of bodies in the EKB and in the main asteroid belt (MAB) are of the same order of magnitude as the estimates obtained in [7-8, 11]. Let us compare the rate of collisions in these belts. There are about 10^6 main-belt asteroids with $d \geq 1$ km. The number of asteroids with $d \geq d_* \geq 1$ km is proportional to $d_*^{-\alpha}$, with α between 2 and 2.5 [25-26]. In the MAB for the ratio s of masses of two colliding bodies, for which a collisional destruction of a larger body usually takes place, equal to 10^4 [27-28], a collisional lifetime T_c of a body with d=1 km is about 1 Gyr [23] (s depends on composition and diameters of objects, a collisional specific energy, and collisional velocity). For α=2 and s=const, T_c does not depend on d. For the EKB with a total mass $M_{EKB} \sim 0.1 m_\oplus$ at d=100 km and $s=10^3$, $T_c \approx 30$ Gyr [15]. At α=2 for $s=10^4$, T_c is smaller by a factor of 4.6 than that for $s=10^3$. For 10^{12} 100-m EKBOs, 1-km EKBO collides with one of 100-m EKBOs on average ones in 3 Gyr. So at s=const the values of T_c for 1-km EKBOs are of the same order of magnitude as those for main-belt asteroids.

The average energy of a collision and, for the same composition of two colliding bodies, also the ratio s needed for destruction of a larger colliding body in the EKB are less by about a factor of $k \approx 20$ than those for the MAB. At α=2 a decrease of s by a factor of 20 corresponds to an increase of T_c by a factor of $k^{2/3} \approx 7.4$. However, as it can be more easy to destruct icy EKBOs than rocky bodies in the MAB, then s can be much larger for the EKB, and collisional lifetimes of small bodies in the EKB can be of the same order as those in the MAB. If some EKBOs are porous, then it may be more difficult to destroy them than icy and even rocky bodies and their collisional lifetimes can be larger than those for main-belt asteroids of the same sizes.

The total mass of "scattered" objects moving in highly eccentric orbits between 40 and 200 AU is considered to be of the same order or greater than M_{EKB}. The mean energy of a collision of a scattered object with an EKBO is greater (probably, on average, by a factor of 4) than that for two colliding EKBOs of the same masses. Therefore, though scattered objects spend a smaller part of their lifetimes at a distance R<50 AU, the probability of a destruction of an EKBO (with 30<a<50 AU) by scattered objects can be of the same order of magnitude as that by EKBOs (it is possible that it can be even larger). The total mass of planetesimals that entered the trans-Neptunian region during the formation of the giant planets could be equal to several tens $m_\oplus$ and this time interval could be about several tens Myr. Besides, the initial mass of the EKB can be much larger ($\sim 10 m_\oplus$) than its present mass. Therefore, TNOs could be even more often destroyed during planet formation than during last 4 Gyr.

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