Formation and migration of trans-Neptunian objects

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Abstract

In our opinion, 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 semi-major axis a>30 AU, but not by the accretion of smaller solid planetesimals. We also suppose that some planetesimals with d~100-1000 km in the feeding zone of the giant planets and with d~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. 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, 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 supposed 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. As migration of TNOs to Jupiter's orbit was investigated by several authors, we integrated the orbital evolution of Jupiter-crossing objects. 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.

Introduction

So far about 800 trans-Neptunian objects (TNOs) are known. Jewitt *et al.* [1] estimated the total mass of the present Edgeworth-Kuiper belt (EKB) for objects with 30≤*a*≤50 AU to be about (0.06-0.25)$m_\oplus$, where $m_\oplus$ is the mass of the Earth. Basing on data obtained by Pioneer 10, Anderson *et al.* [2] concluded this mass to be about 0.1$m_\oplus$. For TNOs with *a*≤50 AU, the average value of eccentricity was evaluated to be e_{av}≈0.1. Objects moving in highly eccentric orbits (mainly with *a*>50 AU) are called "scattered disk objects" (SDOs). Now about 150 SDOs and Centaurs are known. For SDOs e_{av}≈0.5. The total mass of SDOs in eccentric orbits between 40 and 200 AU has been estimated to be about 0.05$m_\oplus$ [3] or 0.5$m_\oplus$ [4].

It was considered by many authors [5-7] 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 [5], which compressed and formed solid planetesimals. In [6] 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*. [8] supposed that initial dimensions of planetesimals from Neptune's feeding zone were much smaller and were about 1 km. According to [9], *the mass of the largest condensation in the region of Neptune could exceed* 2$m_\oplus$. Some scientists considered [10] 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 of Edgeworth-Kuiber belt objects

Formation and collisional evolution of the Edgeworth-Kuiper belt (EKB) was investigated in [11-19]. In these models, the process of accumulation of Edgeworth-Kuiper belt objects (EKBOs) took place at small (~0.001) eccentricities and a massive belt.

Our runs showed [20-21] 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 the accumulation of EKBOs with diameter d>100 km.*

Eneev [22] 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 [23] that *TNOs with d≥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 [24] 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 [24-25] (excitation of TNOs was also considered in [26]). *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 [27-28]. 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.

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 [25, 29-30] 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*. [31-32] by numerical integrations using computers that are at least three orders of magnitude faster, and using much more computer time (our runs for several hundred objects took a few hours on a 1 MHz computer). Several scientists [33-35] studied the formation of the Edgeworth-Kuiper belt by the outward transport of bodies during Neptune's migration. In our old runs the mutual gravitational influence was taken into account by the *method of spheres* (i.e., outside a given sphere the bodies are assumed to move around the Sun in unperturbed Keplerian orbits, whereas inside that sphere we consider the relative motion as a two-body problem). Usually the Tisserand sphere (also called the sphere of action) is used in this method. 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 [21, 36]. An effective method for choosing the pairs of encountering bodies was worked out [21, 37]. The comparison of our old results with those obtained by Thommes *et al*. 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., [25, 38-39]) are close to the results obtained by numerical integration (e.g., [40-41]). Although the method of spheres does not allow us to predict the exact positions of gravitating objects and is not always good for investigations of minor bodies under the gravitational influence of planets [42], it provides the main features of disk evolution, e.g., the mean eccentricities, mean inclinations, and the distributions of bodies in orbital elements. Even for small eccentricities, it is possible to obtain satisfactory results with the use of the method of spheres if we use a larger sphere than the sphere of action. Migration of SDOs to Jupiter's orbit was considered by Emel'yanenko *et al.* [43].

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 in [44-47]. 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 [24]). We suppose [48-49] 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 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.

Collisional evolution of trans-Neptunian objects

Our estimates [21, 50-51] 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 [15-16]. *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 [52-53]. *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 [54-55], *a collisional lifetime* T_c of a body with d=1 km is about 1 *Gyr* [50] (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 [20]. 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 mean energy of a collision is proportional to v_c^2, where v_c is the relative velocity of a collision. For small bodies $v_c \propto (e^2+\sin^2 i)/a$. For the EKB a is greater by a factor of 15 than that for the MAB, and the mean value of $(e^2+\sin^2 i)$ for the EKB is smaller by a factor of 1.4 than that for the MAB. So *the mean 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 smaller by about a factor of* $k \approx 20$ *than those for the MAB*. At α=2 a decrease in 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 SDOs 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 (~10$m_\oplus$) than its present mass. Therefore, *TNOs could be even more often destroyed during planet formation than during last 4 Gyr.*

Orbital variations of EKBOs due to their gravitational interaction were considered in [56-57]. A region of 36<a<39 AU with small e and i is unpopulated, though as shown by Duncan et *al.* [58], it is dynamically stable under the gravitational influence of planets over the age of the solar system. In our opinion [59], the gravitational influence of EKBOs could play an important role in depleting this region (some scientists consider that this region was depopulated due to the variations in semi-major axes of planets).

Total mass of water delivered to Earth during giant planets formation

The total mass of water delivered to the Earth during formation of the giant planets is $\boldsymbol{M_w=M_J P_{JE} k_i}$, where $\boldsymbol{M_J}$ 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 JCO with the Earth during its lifetime, and $\boldsymbol{k_i}$ is the portion of water ices in planetesimals. For M_J=100$m_\oplus$ (where $m_\oplus$ is the mass of the Earth), k_i=0.5, and P_{JE}=$4{\cdot}10^{-6}$, we have $\boldsymbol{M_w=2{\cdot}10^{-4}{\cdot}m_\oplus}$. This value of P is smaller than the mean values obtained in our runs and does not include the `champions' in collision probability. 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 [50-51, 60]). This estimate is greater than those by Morbidelli *et al.* [61] and Levison *et al.* [62], who did not take into account collisions of former comets with the Earth from typical asteroid orbits, but is in accordance with the results by Chyba [63] and Rickman *et al*. [64]. There is the deuterum/hydrogen paradox of Earth's oceans (D/H ratio is different for oceans and comets), but Pavlov *et al.* [65] suggested that solar wind-implanted hydrogen on interplanetary dust partricles provided the necessary low-D/H component of Earth's water inventory. The mass of water delivered to Venus can be of the same order of magnitude. The end of such bombardment could be caused mainly by the planetesimals which became scattered objects, because the dynamical lifetimes of the planetesimals located inside Neptune's orbit usually were less than 0.1 Gyr.

Migration of Jupiter-family comets to the Earth

As the migration of TNOs to Jupiter's orbit was investigated by several authors (e.g., [58, 66]), we have made a series of simulations of the orbital evolution of JCOs under the gravitational influence of planets. We omitted the influence of Mercury (except for Comet 2P/Encke) and Pluto. The orbital evolution of more than 10500 and 15000 JCOs with initial periods P_a<20 yr was integrated with the use of the Bulirsch-Stoer and symplectic methods (BULSTO and RMVS3 codes), respectively. We used the integration package of Levison and Duncan [58].

In the first series of runs (denoted as *n1*) we calculated the evolution of 3100 JCOs moving in initial orbits close to those of 20 real comets with period 5<P_a<9 yr, and in the second series of runs (denoted as *n2*) we considered 13500 JCOs moving in initial orbits close to those of 10 real comets with period 5<P_a<15 yr. In other series of runs, initial orbits were close to those of a single comet (2P, 9P, 10P, 22P, 28P, 39P, or 44P). We investigated the orbital evolution during the dynamical lifetimes of objects (at least until all the objects reached perihelion distance q>6 AU).

In our runs, planets were considered as material points, so literal collisions did not occur. However, based on the orbital elements sampled with a 500 yr step, we calculated the mean probability P of collisions. We define P as P_Σ/N, where P_Σ is the total probability of collisions of N objects with a planet during their lifetimes, the mean time $T=T_\Sigma/N$ during which perihelion distance q of an object was less than the semi-major axis $a_{\rm pl}$ of the planet, the mean time T_d spent in orbits with aphelion distance Q<4.2 AU, and the mean time T_J during which an object moved in Jupiter-crossing orbits. The obtained values of P, T_J, T_d, and T are presented in [68-72]. Results were obtained by the Bulirsch-Stoer method with the integration step error less than $10^{-9}\le\varepsilon\le10^{-8}$ and also with $\varepsilon\le10^{-12}$ and by a symplectic method with an integration step $d_s\le10^{\rm d}$ (days). For these three series of runs, the results obtained were similar (except for probabilities of close encounters with the Sun when they were high).

The results can differ considerably depending on the initial orbits of comets. The values of P for Earth were about $(1\text{-}4)\cdot10^{-6}$ for Comets 9P, 22P, 28P, and 39P. For Comet 10P they were $(6\text{-}10)\cdot10^{-6}$, i.e. greater by almost an order of magnitude than for 9P, though initial orbits of 9P and 10P were close. This is a real difference in dynamics of two comets and is not "luck of the draw" in the integrations. P exceeded 10^{-4} for Comet 2P. For series *n1* and *n2* the value of P for Earth was about $(4\text{-}40)\cdot10^{-6}$ (depending on integrator) and $15\cdot10^{-6}$, respectively.

The probability of a collision with Earth (or with Venus and Mars) for one object that orbited for several Myr with Q<4.2 AU could be much greater than the total probability for hundreds other objects. Some had typical asteroidal and NEO orbits and reached Q<3 AU for several Myr. One object with initial orbit close to that of Comet 88P/Howell after 40 Myr got Q<3.5 AU and moved in orbits with $a\approx2.60\text{-}2.61$ AU, 1.7<q<2.2 AU, 3.1<Q<3.5 AU, $e\approx0.2\text{-}0.3$, and $i\approx5\text{-}10^{\rm o}$ for 650 Myr. The times spent by five specific objects that have large probabilities of collisions with the terrestrial planets while in IEO, Aten (a<1 AU, $Q>0.983$ AU), Al2 (1<a<2 AU, q<1.017 AU), Apollo (a>1 AU, q<1.017 AU), and Amor (1.017<q<1.3 AU) orbits are presented in Table 1.

Table 1. Times (in Myr) spent by five objects in various orbits and probabilities of their collisions with Venus (p_v), Earth (p_e), and Mars (p_m) during their lifetimes T_{lt} (in Myr).

Comet	d_s or ε	IEO	Aten	Al2	Apollo	Amor	T_{lt}	p_v	p_e	p_m
2P	10^d	12	33.6	73.4	75.6	4.7	126	0.18	0.68	0.07
44P	10^d	0	0	11.7	14.2	4.2	19.5	0.02	0.04	0.02
2P	10^{-8}	0.1	83	249	251	15	352	0.224	0.172	0.065
10P	10^{-8}	10	3.45	0.06	0.06	0.05	13.6	0.665	0.344	0.001
113P	6^d	0	0	56.8	59.8	4.8	67	0.037	0.016	0.001

The times spent by 25500 JCOs in Earth-crossing orbits with a<2 AU were due to a few tens (mainly due to less than ten) of objects with high collision probabilities. Among the JCOs considered with BULSTO, only one and two JCOs reached IEO and Aten orbits, respectively.

In the case of close encounters with the Sun (Comets 2P and 96P), the values of probability P_S of collision with the Sun obtained by BULSTO and RMVS3 and at different ε and d_s were different, but all other results were similar, as probabilities of collisions of objects with the terrestrial planets were usually small after their close encounters with the Sun.

The results obtained by direct modelling of collisions with the Sun usually were practically the same if we consider that objects disappear when perihelion distance q becomes less than the radius r_S of the Sun or even several such radii (i.e., we checked $q<k_S \cdot r_S$, where k_S equals 0, 1, or another value).

Trans-Neptunian objects in near-Earth object orbits

Using the results of migration of TNOs obtained by Duncan *et al*. [58], considering the total of $5 \cdot 10^9$ 1-km TNOs with 30<a<50 AU [73], and assuming that the mean time for a body to move in a Jupiter-crossing orbit is about 0.12 Myr, Ipatov [51] found that about $N_{Jo}=10^4$ 1-km former TNOs are now Jupiter-crossers, and 3000 are Jupiter-family comets. Using the total times spent by N simulated JCOs in various orbits, we obtained the following numbers of 1-km former TNOs now moving in several types of orbits:

Table 2. Estimates of the number of 1-km former TNOs now moving in several types of orbits

N	method	series	IEOs	Aten	Al2	Apollo	Amor
3100	BULSTO, RMVS3	n1	0	0	480	1250	900
10000	RMVS3	n2	0	0	400	2500	800
8800	BULSTO	w/o 2P	95	30	230	2600	1560
9352	BULSTO	all	90	770	3700	6500	1700

For example, the number of IEOs $N_{IEOs}=N_{Jo}t_{IEO}/(N_J t_J)$, where t_{IEO} is the total time during which N_J former JCOs moved in IEO orbits, and $N_J t_J$ is the total time during which N_J JCOs moved in Jupiter-crossing orbits. The number of former TNOs in Apollo and Amor orbits can be estimated on the basis of *n1* and *n2* runs. The number of NEOs with diameter d≥1 km is considered to be about 1000-1500. Half of NEOs are Earth-crossers. Even if the number of Apollo objects is smaller by a factor of several than that based on *n1* and *n2* runs, it is comparable to the real number (500-750) of 1-km Earth-crossing objects (half of them are in orbits with a<2 AU), although the latter number does not include those in highly eccentric orbits. The portions of objects in Aten and Al2 orbits are much greater in our 2P runs than in other runs. Our estimates of these portions are very approximate. The above estimates of the portion of former TNOs in NEO orbits are relatively large (up to tens of percents), but it is also possible that the number of TNOs migrating inside solar system could be smaller by a factor of several than it was earlier considered.

Comets are estimated to be active for T_{act}~10^3-10^4 yr. Some former comets can move for tens or even hundreds of Myr in NEO and asteroidal orbits, so, if comets do not disintegrate during such times, than the number of extinct comets can exceed the number of active comets by several orders of magnitude. The rate of a cometary object decoupling from the Jupiter vicinity and transferring to an NEO-like orbit can be increased by a factor of several due to nongravitational effects [74].

Our runs showed that if one observes former comets in NEO orbits, then most of them could have already moved in such orbits for millions of years. Some former comets that have moved in typical NEO orbits for millions or even hundreds of millions of years, and might have had multiple close encounters with the Sun, could have lost their mantles, which caused their low albedo, and so change their albedo (for most observed NEOs, the albedo is greater than that for comets [75]) and would look like typical asteroids, or some of them could disintegrate into mini-comets and dust.

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