Formation and Migration of Trans-Neptunian Objects

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Abstract. Some large trans-Neptunian objects could be formed by the compression of rarefied dust condensations, but not by the accumulation of smaller planetesimals. A considerable portion of near-Earth objects could have come from the trans-Neptunian region. Our runs of the evolution of thousands of orbits of Jupiter-family comets under the gravitational influence of planets showed that former Jupiter-family comets collide with the terrestrial planets mostly from orbits with aphelia located deep inside Jupiter’s orbit.

1. Formation of Trans-Neptunian Objects

Many scientists considered that large trans-Neptunian objects (TNOs) and asteroids were formed by accumulation of smaller (e.g., 1-km) planetesimals. Such process of accumulation of TNOs needs small (∼0.001) eccentricities and a massive belt which probably could not exist during the time needed for such accumulation. Therefore Ipatov (2001) considered that large TNOs and some main-belt asteroids could be formed directly from dust rarefied condensations. It is assumed by many authors that a lot of dust condensations were formed from a dust disk around the forming Sun. These initial condensations coagulated under collisions and formed larger condensations, which compressed and formed solid planetesimals. To our opinion, during the time needed for compression of condensations into planetesimals, some largest final condensations could reach such masses that they formed initial planetesimals with diameter equal to several hundreds kilometers. As in the case of accumulation of planetesimals, there could be a "run-away" accretion of 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.

A small portion of planetesimals from the feeding zone of the giant planets that entered into the trans-Neptunian region could be left in eccentric orbits beyond Neptune and became so called "scattered disk objects" (SDOs). The end of the bombardment of the terrestrial planets could be caused mainly by those planetesimals that had become SDOs. Our estimates (Ipatov 1995, 2001) showed that collisional lifetimes of 1-km TNOs and asteroids are about 1 Gyr. Typical TNOs can be even more often destroyed by SDOs than by other TNOs. Mutual gravitational interactions of TNOs can play a larger role in variations of their orbital elements than collisions.
Figure 1. Time variations in $a$, $q$, $Q$, $e$, $\sin i$ for a former JCO in initial orbit close to that of Comet 10P ($a>1.5$ AU at $t<0.123$ Myr)

Figure 2. Time variations in $a$, $q$, $Q$, $e$, $\sin i$ for a former JCO in initial orbit close to that of Comet 2P

2. Orbital Evolution of Jupiter-Family Comets

The motion of TNOs to Jupiter’s orbit was investigated by several authors (e.g., Levison & Duncan 1997). Proceeding from the total of $5 \cdot 10^9$ 1-km TNOs within $30< a < 50$ AU, assuming the mean time $T_{JCO} \approx 0.13$ Myr for a body to move in a Jupiter-crossing orbit, and using the same formulas and other estimates as those in (Ipatov 2001), we obtain that about $10^4$ of former 1-km TNOs now are Jupiter-crossers. In the present paper we pay the main attention to the migration of Jupiter-crossing objects (JCOs). Our present investigations are based on our runs of the orbital evolution of thousands JCOs under gravitational influence of all planets, except for Mercury and Pluto, for intervals $T_S \geq 10$ Myr (for Comet 2P we also considered Mercury). The integration package by Levison & Duncan (1994) was used. Below we present the results obtained only by the method by Bulirsh and Stoer (BULSTO code), though we also considered the evolution of thousands of objects using a symplectic method. In some cases in our runs (especially, when objects can get close to the Sun) we obtained a considerable difference between the results obtained by BULSTO and a symplectic method. For BULSTO the relative error per integration step was taken (depending on the run) to be less than $\varepsilon$ which was $10^{-9}$, $10^{-8}$, or some intermediate value.

In the first series of runs (denoted as n1) we investigated the orbital evolution of $N=1900$ JCOs moving in initial orbits close to those of 20 real JCOs with period $5 < P \leq 9$ yr. In each of other series of runs we considered initial orbits close to that of one comet (2P, 9P, 10P, 22P, 28P, or 39P). We also studied the evolution of asteroids initially moving in the resonances 3:1 and 5:2 with Jupiter. Approximate values of initial semi-major axes $a$, eccentricities $e$ and inclinations $i$ of considered objects are presented in Table 1. For JCOs we varied only initial
mean anomaly, and for asteroids we varied also initial value of the longitude of the ascending node. Examples of time variations in orbital elements are presented in Figs. 1-2. As these two objects have large probabilities of collisions with the terrestrial planets, they are not included in the Table. In Fig. 3 we present the time in Myr during which 7852 former JCOs had semi-major axes in the interval with a width of 0.005 AU (left) or 0.1 AU (right).

We did not simulate collisions of objects with planets, but basing on orbital elements obtained with a step 500 yr, for all objects we calculated the total impacting probability \( P_{\Sigma} \) and the total time interval \( T_{\Sigma} \) to reach perihelion distance \( q \) less than a semi-major axis of a planet, and then impact probabilities per one object \( P_r = 10^{-6} P_{\Sigma}/N \) and \( T_r = T_{\Sigma}/N \) during \( T_S \) were estimated.

Table 1. Values of \( T \) (in Kyr), \( P_r \), and \( r \) obtained by the BULSTO code (Venus=V, Earth=E, Venus=V)

| \( N \) | \( a \) | \( e \) | \( i \) | \( V \) | \( P_r \) | \( T \) | \( E \) | \( T \) | \( M \) | \( T \) | \( r \) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| \( n1 \) | 1900 | 3.12 | 0.52 | 10 | 2.42 | 4.23 | 4.51 | 7.94 | 6.15 | 30.0 | 0.7 |
| 2P | 501 | 2.22 | 0.85 | 12 | 226 | 504 | 162 | 548 | 69.4 | 579 | 19 |
| 9P | 800 | 3.47 | 0.54 | 4.7 | 1.34 | 1.76 | 3.72 | 4.11 | 0.71 | 9.73 | 1.2 |
| 10P | 2149 | 3.10 | 0.53 | 12 | 28.3 | 41.3 | 35.6 | 71.0 | 10.3 | 169 | 1.6 |
| 22P | 1000 | 6.91 | 0.78 | 14 | 1.7 | 21.8 | 1.9 | 34.7 | 0.44 | 68.9 | 1.9 |
| 28P | 750 | 7.25 | 0.25 | 1.9 | 1.06 | 1.72 | 1.19 | 3.03 | 0.31 | 6.82 | 1.6 |
| 39P | 750 | 7.25 | 0.25 | 1.9 | 1.06 | 1.72 | 1.19 | 3.03 | 0.31 | 6.82 | 1.6 |
| total | 7850 | 4.25 | 0.25 | 1.9 | 1.06 | 1.72 | 1.19 | 3.03 | 0.31 | 6.82 | 1.6 |
| \( 3:1 \) | 288 | 2.5 | 0.15 | 10 | 940 | 1147 | 1223 | 1886 | 371 | 3053 | 2.3 |
| \( 5:2 \) | 288 | 2.82 | 0.15 | 10 | 95.8 | 170 | 160 | 304 | 53.7 | 780 | 1.0 |

In Table 1 we also present the ratio \( r \) of time spent in Apollo orbits \((a>1 \text{ AU}, q=a(1-e)<1.017 \text{ AU})\) at \( e<0.999 \) to that in Amor orbits \((1.017<q<1.33 \text{ AU})\). One object initially moving in orbit close to that of Comet 10P after having Aten-type orbit \((a<1 \text{ AU}, Q=a(1+e)>0.983 \text{ AU})\) during 3 Myr (the probability of its collision with the Earth was 0.34) got orbits with aphelion distance \( Q<0.983 \text{ AU} \) (Fig. 1). The probability of its collision with Venus during \( t \le 50 \text{ Myr} \) was \( \approx 3 \), so more probable that it collided Venus at \( t \approx 15 \text{ Myr} \).

Specific mass of the matter delivered by JCOs to an inner planet (normalized to its mass) turns out to be nearly the same for Earth and Venus though greater for Mars. The total collisional probability with the inner planets was
mainly caused by a small (∼0.01-0.001) fraction of bodies residing in orbits deep inside Jupiter’s orbit for more than 1 Myr. Fifteen considered objects with initial orbits close to those of 10P and 2P moved in Earth-crossing orbits with 1<a<2 AU during more than 0.5 Myr each. At n1, objects moved with periods \( P_a < 10 \) and \( 10 < P_a < 20 \) yr during 11% and 21% of \( T_{JCO} \), respectively. More details of the runs can be found in our papers in http://arXiv.org/archive/astro-ph.

3. Migration of Trans-Neptunian Objects to the Near-Earth Space

In total, 6852 considered JCOs moved during more than 160, 470, 65, 140, and 10 Myr in Amor, Apollo, and Aten orbits, orbits with 1<a<2 AU and \( q<1 \) AU, and orbits with \( Q<0.983 \), respectively. So, if we consider \( 10^4 \) former 1-km TNOs now moving in Jupiter-crossing orbits, then for \( T_{JCO}=0.13 \) Myr their number for the above five types of orbits is about 1600, 4700, 650, 1400, and 100, respectively. As we simulated mainly orbits with large probabilities of collisions with the Earth, the above numbers can be smaller by a factor of several. Mean eccentricities of such orbits are larger and the probabilities of collisions with the terrestrial planets are smaller than those of the observed NEOs. Probably, most of such former TNOs (extinct comets) are not yet observed, as most of the time they move relatively far from the Earth. It is considered that about 750 of 1-km bodies are located in the Earth-crossing orbits (half of them are in orbits with \( a<2 \) AU), although this number does not include those in high eccentric orbits. Our estimates show that, in principle, the trans-Neptunian belt can provide a considerable portion of Earth-crossing objects, at least many of those with \( a>2 \) AU, but, of course, some NEOs came from the main asteroid belt. It may be possible to explore former TNOs near the Earth’s orbit without sending spacecrafts beyond Neptune. Based on the estimated collision probability \( P=6\cdot10^{-6} \) (this value is a little larger than that for \( n1 \), but is smaller by an order of magnitude than \( P=7\cdot10^{-5} \) obtained for 7852 JCOs) and assuming the total mass of planetesimals that ever crossed Jupiter’s orbit is \( \sim100m_\oplus \) (\( m_\oplus \) is mass of the Earth), we found that the total mass of bodies impacted on the Earth is \( 6\cdot10^{-4}m_\oplus \). If ices composed only a half of this mass, then the total mass of ices that were delivered to the Earth from the feeding zone of the giant planets turns out by the factor of 1.5 greater than the mass of the Earth oceans. Ancient oceans on Mars and Venus could be also large.

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