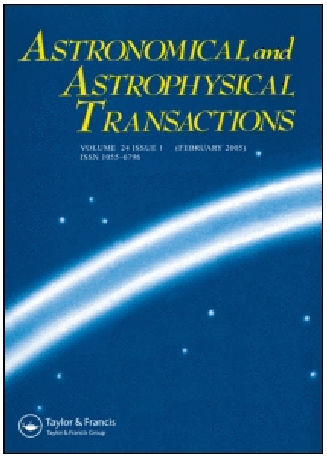

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Migration of trans-Neptunian objects to the Earth

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Migration of trans-Neptunian objects to the Earth

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The orbital evolution of about 30 000 Jupiter-family comets under the gravitational influence of planets was investigated. For initial orbital elements close to those of Comets 2P, 10P, 44P and 113P, a few objects had Earth-crossing orbits with semimajor axes $a < 2$ AU and moved in such orbits for more than 1 M years (up to tens or even hundreds of megayears). Four objects even possessed inner-Earth orbits (with aphelion distance $Q < 0.983$ AU) and Aten orbits for megayears. Our results show that the trans-Neptunian belt can provide a significant fraction of near-Earth objects, or that the number of trans-Neptunian objects migrating inside the Solar System could be smaller than was considered earlier, or that most 1 km former trans-Neptunian objects that had near-Earth object orbits disintegrated into minicomets and dust during a small part of their dynamic lifetimes if these lifetimes are not small.

Keywords: Migration; trans-Neptunianian objects; Earth; Orbital evolution

1. Introduction

It is considered by many researchers that the Tunguska object could be a small comet or the debris of a comet. The Tunguska event, which occurred in 1908, was caused by a body with a diameter of about 60–70 m. Its trinitrotoluence equivalent effect is estimated to be 10–40 Mton and corresponds to that of the largest nuclear bombs. The number of such objects in near-Earth space exceeds 100 000. Below we discuss that many near-Earth objects (NEOs) could be former comets.

The lifetimes of NEOs are small compared with the age of the Solar System. It is considered that celestial bodies migrate to the near-Earth space from the main asteroid and Edgeworth–Kuiper belts, the Oort and Hills clouds, and the Trojan swarms, but different workers considered different bodies as the main sources of NEOs. Our reviews of papers on the migration of asteroids and comets to NEO orbits can be found in [1–4]. The problem of the migration of bodies to the Earth can be divided into several subproblems: migration under the gravitational influence of planets to the near-Earth space, evolution of the orbits of NEOs, and their impacts with the Earth. Because of collisions, mutual gravitational influence and the Yarkovsky effect,

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bodies of the asteroid and trans-Neptunian belts can be transferred from their native regions to planet-crossing orbits.

Trans-Neptunian objects (TNOs) are considered to be the main source of short-period comets. As migration of TNOs to Jupiter's orbit has been investigated by several researchers, we have made series of runs of the orbital evolution of Jupiter-crossing objects under the gravitational influence of planets.

2. Migration of Jupiter-family comets to the Earth

The orbital evolution of about 30 000 Jupiter-crossing objects (JCOs) with initial periods $P_a < 20$ years was integrated [2–4]. The gravitational influences of all planets except for Pluto, and sometimes Mercury, were considered. 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 periods 5 years $< P_a <$ 9 years, and in the second series of runs (denoted as $n2$) we considered 14 000 JCOs moving in initial orbits close to those of ten other real comets with periods 5 years $< P_a <$ 15 years. 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 dynamic lifetimes of objects (at least until all the objects reached the perihelion distance $q > 6$ AU). In our runs, planets were considered as material points; so literal collisions did not occur. However, on the basis of the orbital elements sampled with a 500 year step, we calculated the mean probability P of collisions.

Results were obtained by the Bulirsch–Stoer method with the integration step error less than $10^{-9} \leq \varepsilon \leq 10^{-8}$ and also with $\varepsilon \leq 10^{-12}$ and by a symplectic method with an integration step $d_s \leq 10$ 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 $(1-4) \times 10^{-6}$ for Comets 9P, 22P, 28P and 39P. For Comet 10P they were $(6–10) \times 10^{-6}$ and exceeded 10^{-4} for Comet 2P. With the $n1$ and $n2$ runs, for Earth, $P > 4 \times 10^{-4}$ and $P > 10^{-5}$ respectively.

The obtained results showed that the main fraction of the probability of collisions of former JCOs with the terrestrial planets is due to a small (about 0.1–1%) fraction of objects that moved during several Megayears in orbits with aphelion distances $Q < 4.7$ AU. Some of them had typical NEO orbits and could have $Q < 3$ AU for millions of years.

The ratio of the mean probability of a JCO with $a > 1$ AU with a planet to the mass of the planet was greater for Mars by several-times than those for Earth and Venus. Four considered former JCOs even had inner-Earth orbits (with $Q < 0.983$ AU) or Aten orbits ($a < 1$ AU; $Q > 0.983$ AU) for Megayears. One former JCO had Aten orbits for more than 3 M years, but the probability of its collision with the Earth was greater than that for thousands of other former JCOs considered. This object also moved during about 10 Myears (before its collision with Venus) in inner-Earth orbits and during this time the probability of its collision with Venus was greater than the total probability of collisions of thousands of other considered JCOs with Earth and Venus.

For series $n1$ with a symplectic method, the probability of a collision with Earth for one object with initial orbit close to that of Comet 44P was 88.3% of the total probability for 1200 objects from this series, and the total probability for 1198 objects was only 4%. The probabilities of collisions of one object with Earth and Venus could be greater than that for thousands of other objects combined. With the Bulirsch-Stoer method, six and nine objects, from the 10P and 2P series respectively, moved in Apollo orbits with $a < 2$ AU for at least

0.5 Myears each, and five of these remained in such orbits for more than 5 Myears each. Only two objects in series $n2$ had Apollo orbits with $a < 2$ AU for more than 1 Myear.

The number of JCOs considered was greater than that considered by Bottke *et al.* [5] by an order of magnitude; so that is why these scientists did not obtain orbits with $a < 2$ AU. Note that Ipatov [6] obtained migration of JCOs into inner-Earth and Aten orbits using the method of spheres.

One object with an initial orbit close to that of Comet 88P after 40 Myears had $Q < 3.5$ AU and moved in orbits with $a \approx 2.60$–2.61 AU, 1.7 AU $< q <$ 2.2 AU, 3.1 AU $< Q <$ 3.5 AU, $e \approx 0.2$–0.3 and $i \approx 5$–$10°$ for 650 Myears. Another object (with initial orbit close to that of Comet 94P) moved in orbits with $a \approx 1.95$–2.1 AU, $q > 1.4$ AU, $Q < 2.6$ AU, $e \approx 0.2$–0.3 and $i \approx 9$–$33°$ for 8 Myears (and it had $Q < 3$ AU for 100 Myears). So JCOs can rarely have typical asteroid orbits and move in them for Megayears. In our opinion, it could be possible that Comet 133P (Elst–Pizarro) which moves in a typical asteroidal orbit was earlier a JCO and it circled its orbit also as a result of non-gravitational forces.

3. Trans-Neptunian objects in near-Earth object orbits

Using our results of the orbital evolution of JCOs and the results of migration of TNOs obtained by Duncan *et al.* [7] and considering the total of 5×10^9 TNOs of 1 km diameter with 30 AU $< a <$ 50 AU, we obtained [4] that the number of 1 km former TNOs in NEO orbits can be of the same order of magnitude as the number of 1 km NEOs, or that the number of TNOs migrating inside the Solar System could be smaller than was considered earlier, or that most 1 km former TNOs that had NEO orbits disintegrated into minicomets and dust during a small part of their dynamic lifetimes if these lifetimes are not small. The number of extinct comets can exceed the number of active comets by several orders of magnitude. Some former comets could have lost their mantles, which caused their low albedo; this changed their albedo and so they would look like typical asteroids, or some of them could disintegrate into minicomets and dust.

Using $P = 4 \times 10^{-6}$ (this value is smaller than the mean value of P obtained in our runs) and assuming that the total mass of planetesimals that ever crossed Jupiter's orbit is about $100m_{\rm E}$, where $m_{\rm E}$ is the mass of the Earth, we obtained that the total mass of water delivered from the feeding zone of the giant planets to the Earth could be about the mass of Earth oceans.

4. Conclusions

Some Jupiter-family comets (JFCs) can reach typical NEO orbits and remain there for millions of years. While the probability of such events is small (about 0.1%), nevertheless the majority of collisions of former JFCs with the terrestrial planets are due to such objects. Most former TNOs that have typical NEO orbits moved in these orbits for millions of years; so during most of this time they were extinct comets. If those former JFCs that had NEO orbits for millions of years did not disintegrate during this time, there could be many extinct comets among the NEOs.

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