

Migration of comets to the terrestrial planets

Sergei I. Ipatov^{1,2} and John C. Mather³

¹Department of Terrestrial Magnetism, Carnegie Institution of Washington
Washington DC, USA
email: siipatov@hotmail.com
http://www.dtm.ciw.edu/ipatov

²Space Research Institute, Moscow, Russia

³LASP, NASA/Goddard Space Flight Center, Greenbelt, USA
email: John.C.Mather@nasa.gov

Abstract. We studied the orbital evolution of objects with initial orbits close to those of Jupiter-family comets (JFCs), Halley-type comets (HTCs), and long-period comets, and the probabilities of their collisions with the planets. In our runs the probability of a collision of one object with the Earth could be greater than the sum of probabilities for thousands of other objects. Even without the contribution of such a few objects, the probability of a collision of a former JFC with the Earth during the dynamical lifetime of the comet was greater than 4×10^{-6} . This probability is enough for delivery of all the water to Earth's oceans during the formation of the giant planets. The ratios of probabilities of collisions of JFCs and HTCs with Venus and Mars to the mass of the planet usually were not smaller than that with Earth. Among 30 000 considered objects with initial orbits close to those of JFCs, a few objects got Earth-crossing orbits with semimajor axes $a < 2$ AU and aphelion distances $Q < 4.2$ AU, or even got inner-Earth ($Q < 0.983$ AU), Aten, or typical asteroidal orbits, and moved in such orbits for more than 1 Myr (up to tens or even hundreds of Myr). From a dynamical point of view, the fraction of extinct comets among near-Earth objects can exceed several tens of percent, but, probably, many extinct comets disintegrated into mini-comets and dust during a smaller part of their dynamical lifetimes.

Keywords. Transport of comets; transport of meteorites

1. Introduction

Farinella *et al.* (1993), Bottke *et al.* (2002), Binzel *et al.* (2002), Weissman *et al.* (2002) believe that asteroids are the main source of near-Earth objects (NEOs). Wetherill (1988) supposed that half of NEOs are former short-period comets. Trans-Neptunian objects (TNOs) can migrate to the near-Earth space. Duncan *et al.* (1995) and Kuchner *et al.* (2002) investigated the migration of TNOs to Neptune's orbit, and Levison & Duncan (1997) studied their migration from Neptune's orbit to Jupiter's orbit. Levison *et al.* (2006) studied the formation of Encke-type objects. More references on papers devoted to the migration of bodies from different regions of the solar system to the near-Earth space can be found in our previous publications on this problem (Ipatov 1995, 1999, 2000, 2001; Ipatov & Hahn 1999; Ipatov & Mather 2003, 2004a,b, 2006a). As the migration of TNOs to Jupiter's orbit was considered by several authors, Ipatov (2002) and Ipatov & Mather (2003, 2004a,b, 2006a) paid particular attention to the orbital evolution of Jupiter-crossing objects (JCOs), considering a larger number of JCOs than before.

In the present paper, we summarize our studies of migration of cometary objects into NEO orbits, paying particular attention to the probabilities of collision of cometary objects with the terrestrial planets. These studies are based on our previous runs and on

some new runs. Earlier we did not consider the evolution of orbits of Halley-type comets and long-period comets and did not study the probabilities of collisions of different comets with the giant planets. Though some runs used here are the same as earlier, the discussion on migration of small bodies based on these runs is different.

2. Initial data

Ipatov & Mather (2003, 2004a,b, 2006a) integrated the orbital evolution of about 30 000 objects with initial orbits close to those of Jupiter-family comets (JFCs). We considered the gravitational influence of the planets, but omitted the influence of Mercury (except for Comet 2P/Encke) and Pluto. In about a half of the runs we used the method by Bulirsh-Stoer (1966) (BULSTO code), and in other runs we used a symplectic method (RMVS3 code). The integration package of Levison & Duncan (1994) was used. Usually we investigated the orbital evolution during the dynamical lifetimes of objects (until all the objects reached 2000 AU from the Sun or collided with the Sun).

In the first series of runs (denoted as $n1$) we calculated the orbital evolution of 3 100 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 13 500 initial orbits close to those of 10 real JFCs with period $5 < P_a < 15$ yr. We selected comets with the above periods among JFCs with numbers between 7 and 75 for $n1$ and with numbers between 77 and 113 for $n2$. In other series of runs, initial orbits were close to those of a single comet (2P/Encke, 9P/Tempel 1, 10P/Tempel 2, 22P/Kopff, 28P/Neujmin 1, 39P/Oterma, or 44P/Reinmuth 2). Comet 2P/Encke is the only comet with aphelion distance $Q < 4.2$ AU; comets 28P/Neujmin 1 and 44P/Reinmuth 2 are typical comets with semimajor axis $a \approx 7$ AU, and other four above comets are typical comets with $a \sim 3 - 4$ AU. In order to compare the orbital evolution of comets and asteroids, we also studied the orbital evolution of 1 300 test asteroids initially moving in the 3:1 and 5:2 resonances with Jupiter.

In our recent runs we also considered objects started from orbits of test long-period comets (initial eccentricity $e_o = 0.995$, $q_o = a_o(1 - e_o) = 0.9$ AU or $q_o = 0.1$ AU, initial inclination i_o between 0 and 180° in each run, objects started at perihelion; these runs are denoted as *lpc* runs) and test Halley-type comets ($a_o = 20$ AU, i_o between 0 and 180° in each run, objects started at perihelion; in some runs $e_o = 0.975$ and $q_o = 0.5$ AU, in other runs $e_o = 0.9$ and $q_o = 2$ AU; these runs are denoted as *htc* runs).

In our runs, planets were considered as material points, so literal collisions did not occur. However, using the algorithm suggested by Ipatov (1988, 2000) with the correction that takes into account a different velocity at different parts of the orbit (Ipatov & Mather 2003), and based on all orbital elements sampled with a 500 yr step, we calculated the mean probability P of collisions of migrating objects with a planet. We define P as P_Σ/N , where P_Σ is the probability for all N objects of a collision of an object with a planet. If it is not mentioned specially, all probabilities below are considered for dynamical lifetimes of objects. Note that our algorithm differed from the Öpik's scheme, and included calculations of a synodic period and the region where the distance between the "first" orbit and the projection of the "second" orbit onto the plane of the "first" orbit is less than the sphere of action (i.e., the Tisserand sphere). The code includes calculations of the probability that both objects are on the same line of sight from the Sun within the above region, of the difference in probabilities for planar and spatial models, and of the probability of a collision inside the sphere.

For BULSTO runs, the integration step error was less than ϵ , where ϵ varied between 10^{-13} and 10^{-8} (most of the runs were made for ϵ equal to 10^{-8} and 10^{-9}), and for a

RMVS3 runs an integration step d_s varied from 0.1 to 30 days (most runs were made for $d_s=10$ days). In a single run with N (usually $N = 250$) objects, ϵ or d_s was constant. Results obtained with the use of different methods of integration at different d_s or ϵ were similar (see Ipatov & Mather 2003 for details), except for probabilities of collisions with the Sun in such runs when this probability was large (for comets 2P/Encke and 96P/Machholz 1 from $n2$ series, and the 3:1 resonance with Jupiter). Probabilities of collisions of bodies with planets were close for different integrators even in the latter case because soon after close encounters with the Sun, bodies were ejected into hyperbolic orbits or moved in highly inclined orbits. In most “cometary” runs, the fraction P_{Sun} of comets collided with the Sun was less than 0.02; P_{Sun} exceeded 0.05 for some *htc* runs, and most of objects in 2P/Encke runs collided with the Sun.

Levison showed that it is difficult to detect solar collisions in any numerical integrator, so he removed objects with perihelion distance $q < q_{\min}$. Our runs were made for direct modeling of collisions with the Sun, but we studied what happens if we consider q_{\min} equal to k_S radii r_S of the Sun. We obtained that the mean probabilities of collisions of bodies with planets, lifetimes of the objects that spent millions of years in Earth-crossing orbits, and other obtained results were practically the same if we consider that objects disappear when 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 1, 2, or another value). The only noticeable difference was for Comet 96P/Machholz 1 from the $n2$ series, and a smaller one was for Comet 2P/Encke, but the results of such runs were not included in our statistics. The eccentricity and inclination of Comet 96P/Machholz 1 are large, so usually even for these $n2$ runs, the collision probabilities of objects with the terrestrial planets were not differed by more than 15% at $k_S = 0$ and $k_S = 1$. Among more than a hundred considered runs, there were three runs, for each of which at $k_S = 0$ a body in an orbit close to that of Comet 96P/Machholz 1 was responsible for 70-75% of collision probabilities with the Earth, and for $k_S = 1$ a lifetime of such body was much less than for $k_S = 0$. Nevertheless, for all ($\sim 10^4$) objects from $n2$ series, at $k_S = 0$ the probabilities of collisions with the terrestrial planets were close to those at $k_S = 1$, even if we consider the above runs. The difference for times spent in Earth-crossing orbits is greater than that for the probabilities and is about 20%. For all runs of the 2P/Encke series, the difference in time spent in orbits with $Q < 4.7$ AU for $k_S = 0$ and for $k_S = 1$ was less than 4%. In the 2P/Encke series of runs (and also for the 3:1 resonance with Jupiter), at $k_S = 0$ we sometimes got orbits with $i > 90^\circ$, but practically there were no such orbits at $k_S \geq 1$ (Ipatov & Mather 2004a,b). Among the objects with initial orbits close to that of Comet 96P/Machholz 1, we found one object which also got $i > 90^\circ$ for 3 Myr. Inclinations of other such objects did not exceed 90° .

3. Computer simulations of the migration of comets to near-Earth orbits

Some migrating JCOs got Earth-crossing orbits. Usually they spent in such orbits only a few thousands years, but a few objects moved in Earth-crossing orbits with aphelion distances $Q < 4.2$ AU for millions of years. The total times which 30 000 considered objects started from JFC orbits spent in Earth-crossing orbits with $a < 2$ AU were due to a few tens of objects, but mainly only to a few of them. In this section we consider only these few objects. With BULSTO at $10^{-9} \leq \epsilon \leq 10^{-8}$, six and nine objects, respectively from the 10P/Tempel 2 and 2P/Encke series, moved into Apollo orbits with $a < 2$ AU (*A12* orbits) for at least 0.5 Myr each, and five of them remained in such orbits for more than 5 Myr each. Among the JFCs considered with BULSTO, only one and two JFCs

reached inner-Earth orbits (IEO, $Q < 0.983$ AU) and Aten orbits, respectively. Only two objects in series $n2$ got $A/2$ orbits during more than 1 Myr. For the $n1$ series of runs, while moving in JCO orbits, objects had orbital periods $P_a < 20$ yr (JFCs) and $20 < P_a < 200$ yr (Halley-type comets) for 32% and 38% of the mean value T_J ($T_J = 0.12$ Myr) of the total time spent by one object in Jupiter-crossing orbits, respectively.

Four considered former JFCs even got IEO or Aten orbits for Myrs. Note that Ipatov (1995) obtained migration of JCOs into IEO orbits using the method of spheres to consider the gravitational influence of planets. In our BULSTO runs, one former JCO, which had an initial orbit close to that of 10P/Tempel 2, moved in Aten orbits for 3.45 Myr, and the probability of its collision with the Earth from such orbits was 0.344. It also moved for about 10 Myr in IEO orbits before its collision with Venus, and during this time the probability of its collision with Venus was $P_V = 0.655$. The above probabilities are greater than the total probabilities for 10^4 other JCOs. Another object (from the 2P BULSTO run) moved in highly eccentric Aten orbits for 83 Myr, and its lifetime before collision with the Sun was 352 Myr. Its probability of collisions with Earth, Venus, and Mars during its lifetime was 0.172, 0.224, and 0.065, respectively. With RMVS3 at $d_s \leq 10$ days for the 2P run, the probability of collisions with Earth for one object was greater by a factor of 30 than for 250 other objects. For series $n1$ with RMVS3, the probability of a collision with the Earth for one object with an initial orbit close to that of Comet 44P/Reinmuth 2 was 88% of the total probability for 1200 objects from this series, and the total probability for 1198 objects was only 4%. For series 44P/Reinmuth 2 with $N=1500$ there were no objects with $a < 2$ AU and $q < 1$ AU, though the 44P object in $n1$ run spent 11.7 Myr in such orbits. For series $n2$ with RMVS3, we obtained one object with an initial orbit close to that of Comet 113P/Spitaler with relatively large values of probabilities of collisions with Earth and Venus. This object is responsible for 10% of the total collision probability with Earth for all $n2$ objects, but most of the time spent by all these objects in orbits with $a < 2$ AU and $q < 1$ AU are due to this object. Though about a half of 30 000 considered objects belong to series $n2$, most of objects that spent a long time in Earth-crossing orbits with $Q < 4.2$ AU belong to other series of runs.

After 40 Myr one considered object with an initial orbit close to that of Comet 88P/Howell (from $n2$ RMVS3 runs) got $Q < 3.5$ AU, and it moved in orbits with $a = 2.60 - 2.61$ AU, $1.7 < q < 2.2$ AU, $3.1 < Q < 3.5$ AU, eccentricity $e = 0.2 - 0.3$, and inclination $i = 5 - 10^\circ$ for 650 Myr. Another object (with an initial orbit close to that of Comet 94P/Russel 4) moved in orbits with $a = 1.95 - 2.1$ AU, $q > 1.4$ AU, $Q < 2.6$ AU, $e = 0.2 - 0.3$, and $i = 9 - 33^\circ$ for 8 Myr (and it had $Q < 3$ AU for 100 Myr). So JFCs can very rarely get typical asteroid orbits and move in them for Myrs. In our opinion, it can be possible that Comet 133P/Elst-Pizarro moving in a typical asteroidal orbit (Hsieh & Jewitt 2006) was earlier a JFC and it circulated its orbit also due to non-gravitational forces. JFCs got typical asteroidal orbits less often than NEO orbits.

Levison *et al.* (2006) argued that our obtained orbits with $a \approx 1$ AU were due to the fact that collisions of objects with terrestrial planets were not taken into account in our runs and such orbits were caused by too close encounters of objects with planets which really result in collisions. Based on the orbital elements obtained in our runs, we can conclude that probabilities of collisions of migrating bodies with planets before bodies got orbits with $a < 2$ AU were very small and the reason of the transformations of orbits was not caused by such close encounters of objects with the terrestrial planets that really resulted in collisions with the planets. Some real probabilities of collisions of bodies moving in orbits with $a < 2$ AU with the terrestrial planets were only after bodies had already got such orbits and moved in them for tens or hundreds of Myr. Other

scientists did not obtain the migration of JCOs into orbits with $a \approx 1$ AU because they considered other initial data. In series n_2 with 13 500 objects, we also did not obtain orbits with $a \approx 1$ AU and obtained only two orbits with $a < 2$ AU (the latter orbits were also obtained by Levison *et al.* 2006). For other series of runs, we paid particular attention to those initial data for which migrating objects could spend a long time inside Jupiter's orbit.

4. Cometary objects in NEO orbits

Based on the results of migration of JFCs with initial orbits close to the orbit of Comet P/1996 R2 Lagerkvist obtained by Ipatov & Hahn (1999) (for these runs with about a hundred objects, there were no objects which spent a long time in Earth-crossing orbits), Ipatov (1999, 2001) found that 10 – 20% or more of all 1-km Earth-crossers could have come from the Edgeworth-Kuiper belt into Jupiter-crossing orbits. Using our results of the orbital evolution of 30 000 JCOs and the results of migration of TNOs obtained by Duncan *et al.* (1995) and considering the total of 5×10^9 1-km TNOs with $30 < a < 50$ AU, Ipatov & Mather (2003, 2004a,b) estimated the number of 1-km former TNOs in NEO orbits. The results of their runs testify in favor of at least one of these conclusions: (1) the portion of 1-km former TNOs among NEOs can exceed several tens of percents, (2) the number of TNOs migrating inside the solar system could be smaller by a factor of several than it was earlier considered, (3) most of 1-km former TNOs that had got NEO orbits disintegrated into mini-comets and dust during a smaller part of their dynamical lifetimes if these lifetimes are not small. All these three scenarios could take place. We consider that the role of disintegration may be more valuable and most of former comets that could move inside Jupiter's orbit for millions of years really were disintegrated. As the number of TNOs, their rate of migration inside the solar system, and lifetimes of former comets before their disruption are not well known, the estimates of the fraction of former TNOs among NEOs are very approximate.

Disintegrated comets could produce a lot of mini-comets and dust. Therefore there could be a lot of cometary dust among zodiacal particles, some of them were produced by high eccentricity comets (such as Comet 2P/Encke). The same conclusion about cometary dust was made by Ipatov *et al.* (2006a,b) based on analysis of spectra of the zodiacal light. Frank *et al.* (1986a,b) concluded that there is a large influx of small comets into the Earth's upper atmosphere.

It is known (Merline *et al.* 2002; Noll 2006; Pravec *et al.* 2006) that about 15% of NEOs and 2-3% of main-belt asteroids are binaries. We can suppose that the fraction of NEO binaries is greater for those NEOs which are extinct comets than those for NEOs that came from the main asteroid belt. Comets more often split into smaller parts than asteroids, and probably there are former comets even among binary main-belt asteroids. Besides, if initial (before collisional destruction) small bodies were formed by compression of dust condensations, then the fraction of binary objects is greater for greater distances of the place of origin of bodies from the Sun (Ipatov 2004).

Comets are estimated to be active for $T_{act} \sim 10^3 - 10^4$ yr. T_{act} is smaller for closer encounters with the Sun (Weissman *et al.* 2002), so for Comet 2P/Encke it is smaller than for other JFCs. If considered as material points, some former comets can move for tens or even hundreds of Myr in NEO orbits, so the number of extinct comets can exceed the number of active comets by several orders of magnitude. The mean time spent by Encke-type objects in Earth-crossing orbits was ≥ 0.4 Myr. This time corresponds to $\geq 40 - 400$ extinct comets of this type if we consider that Encke-type active comet is not an exceptional event in the history of the solar system. Note that the diameter of Comet

2P/Encke is about 5 – 10 km, so the number of 1-km Earth-crossing extinct Encke-type comets can be greater by a factor of 25-100 than the above estimate for Encke-size comets and can exceed 1 000 for such estimates. The rate of a cometary object decoupling from the Jupiter vicinity and transferring to a NEO-like orbit can be increased by a factor of several due to nongravitational effects (Harris & Bailey 1998; Asher *et al.* 2001; Fernández & Gallardo 2002). The role of the Yarkovsky and YORP effects on dynamics of asteroids was summarized by Bottke *et al.* (2006).

Dynamical models of the NEO population considered by Bottke *et al.* (2002) allowed 6% of dead comets. From measured albedos, Fernández *et al.* (2001) concluded that the fraction of extinct comets among NEOs and unusual asteroids is significant (9%). Rickman *et al.* (2001) and Jewitt & Fernández (2001) considered that dark spectral classes that might include the ex-comets are severely under-represented and comets played an important and perhaps even dominant role among all km-size Earth impactors. Binzel & Lupishko (2006) studied albedos and spectra of NEOs and concluded that $15 \pm 5\%$ of the entire NEO population may be composed by extinct or dormant comets. Harris & Bailey (1998) concluded that the number of cometary asteroids becomes comparable to the number of bodies injected from the main asteroid belt if one considers non-gravitational effects. Typical comets have larger rotation periods than typical NEOs (Binzel *et al.* 1992; Lupishko & Lupishko 2001), but, while losing considerable portions of their masses, extinct comets can decrease these periods.

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 (or at least hundreds of thousands) of years. Some former comets that have moved in typical NEO orbits for 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 (Fernández *et al.* 2001) and would look like typical asteroids.

5. Probabilities of collisions of comets with planets

The probability of a collision of one celestial body with a planet can be greater than the total probability for thousands of objects with almost the same initial orbit. All probabilities considered below were calculated for dynamical lifetimes of objects. A few JCOs (mentioned in Section 3) with the highest probabilities with planets were not included in the statistics presented below. For series *n1*, the probability P_E of a collision of an object with the Earth (during a dynamical lifetime of the object) was about 4.5×10^{-6} and 4.8×10^{-6} for BULSTO and RMVS3 runs, respectively (but for RMVS3 it is by an order of magnitude greater if we consider one more object with the highest probability). For series *n2*, the mean value of P_E was $\sim (10 - 15) \times 10^{-6}$ for BULSTO and RMVS3 runs.

Probabilities of collisions of JFCs with planets were different for different comets. The probability of a collision of Comet 10P/Tempel 2 with the Earth was 36×10^{-6} and 22×10^{-6} for BULSTO and RMVS3 runs, respectively ($P_E = 140 \times 10^{-6}$ if we include objects with high collision probabilities). For 2P/Encke runs, P_E was relatively large: $\approx (1-5) \times 10^{-4}$. For most other considered JFCs, $10^{-6} \leq P_E \leq 10^{-5}$. For Comets 22P/Kopff and 39P/Oterma, $P_E \approx (1 - 2) \times 10^{-6}$, and for Comets 9P/Tempel 1, 28P/Neujmin 1, and 44P/Reinmuth 2, $P_E \approx (2 - 5) \times 10^{-6}$. The Bulirsh-Stoer method of integration and a symplectic method gave similar results. Values of P_E were about $(0.5 - 2) \times 10^{-6}$ for *htc* runs, with greater values for smaller q_o . For *lpc* runs, $P_E = 0.6 \times 10^{-6}$ at $q_o = 0.9$ AU and $P_E = 0.25 \times 10^{-6}$ at $q_o = 0.1$ AU. Dynamical lifetimes of some objects in *htc* and

lpc runs exceeded several Myr. Note that we considered collision probabilities for objects starting from different types of orbits, but a type of orbit (e.g., JFCs, HTC, and LPC) can change during the orbital evolution of objects.

The fraction of asteroids migrated from the 3:1 resonance with Jupiter that collided with the Earth was greater by a factor of several than that for the 5:2 resonance ($P_E \sim 10^{-3}$ and $P_E \sim (1-3) \times 10^{-4}$, respectively). The probabilities of collisions with the Earth for resonant asteroids (per one object) were about two orders of magnitude greater than those for typical JFCs. The difference in P_E for the asteroids and TNOs is greater than that for the asteroids and typical JFCs, as only about 1/3 of TNOs that had leaved the trans-Neptunian belt reached Jupiter's orbit (Duncan *et al.* 1995). The present mass of the Edgeworth-Kuiper belt is considered to be about two orders of magnitude greater than that of the main asteroid belt. For dust particles started from comets and asteroids, P_E was maximum for diameters $d \sim 100 \mu\text{m}$ (Ipatov *et al.* 2004; Ipatov & Mather 2006a,b). These maximum values of P_E were usually (exclusive for 2P/Encke runs) greater at least by an order of magnitude than the values for parent comets.

The probabilities P_V of collisions of JFCs and HTCs with Venus usually did not differ by more than a factor of 2 from those with Earth. For 2P/Encke runs, they were greater than those with Earth, but in most of other runs they were smaller. The probabilities P_M of collisions of JFCs and HTCs with Mars usually were smaller by a factor of 3-6 (10 for the 2P/Encke runs) than those with Earth, i.e., Mars accreted more cometary bodies than Earth per unit of mass of the planet. For *lpc* runs, the values of P_E and P_V can differ by a factor of 3, and $P_E/P_M \sim 7-10$.

For most our runs, the probability P_J of a collision of a JFC with Jupiter (during a dynamical lifetime of the comet) was ~ 0.01 . Usually it was less than 0.03, though it can be up to 0.06 in a single run. Due to resonances, the actual values of P_J can be smaller than those in our runs. The mean time T_J spent by objects in Jupiter-crossing orbits was 0.12 Myr for *n1* runs. So the collision frequency of an object started from a JFC orbit and moving in a Jupiter-crossing orbit is about 10^{-7} yr^{-1} . Though T_J can be a little greater for 2P/Encke runs than for *n1* and *n2* runs, and it can exceed 1 Myr for *htc* runs, P_J was only about 5×10^{-4} for some 2P/Encke and *htc* runs. In other 2P/Encke runs, P_J can be greater or smaller by a factor of 20 than the above value. For *lpc* runs, P_J was smaller by an order of magnitude than that for *htc* runs though T_J did not differ much.

Probabilities P_S of collisions of objects from *n1* and *n2* runs with Saturn typically were smaller by an order of magnitude than those with Jupiter, and collision probabilities with Uranus and Neptune typically were smaller by three orders of magnitude than those with Jupiter. The ratio of probabilities of collisions of bodies with different giant planets, for a pair of planets can vary by more than an order of magnitude from run to run. As only a small fraction of comets collided with all planets during dynamical lifetimes of comets, the orbital evolution of comets for the considered model of material points was close to that for the model when comets collided with a planet are removed from integrations.

6. Delivery of water and volatiles to planets

Using $P_E = 4 \times 10^{-6}$ (this value is smaller than the mean value of P_E obtained in our runs for JFCs) and assuming that the total mass of planetesimals that ever crossed Jupiter's orbit is about $100m_\oplus$ (Ipatov 1987, 1993), where m_\oplus is the mass of the Earth, we obtain that the total mass of water delivered from the feeding zone of the giant planets to the Earth could be about the mass of water in Earth's oceans. We considered that the fraction k_w of water in planetesimals equaled 0.5. For present comets $k_w < 0.5$ (Jewitt 2004), but it is considered that k_w could exceed 0.5 for planetesimals. The fraction of

the mass of the planet delivered by JFCs and HTC's can be greater for Mars and Venus than that for the Earth. This larger mass fraction would result in relatively large ancient oceans on Mars and Venus. The conclusion that planetesimals from the zone of the giant planets could deliver all the water to the terrestrial oceans was also made by Ipatov (2001) and Marov & Ipatov (2001) on the basis of runs by Ipatov & Hahn (1999).

The above estimate of water delivery by cometary bodies to the Earth is greater than those by Morbidelli *et al.* (2000) and Levison *et al.* (2001), but is in accordance with the results by Chyba (1989) and Rickman *et al.* (2001). The larger value of P_E we have calculated compared to those argued by Morbidelli *et al.* (2000) ($P_E \sim (1-3) \times 10^{-6}$) and Levison *et al.* (2001) ($P_E = 4 \times 10^{-7}$) is caused by the fact that in our runs we considered other initial orbits and a larger number of JCOs. Levison *et al.* (2001) did not take into account the influence of the terrestrial planets, so probably that is why his values of P_E are even smaller than those by Morbidelli *et al.* (2000). The latter authors used results of integrations of objects initially located beyond Jupiter's orbit. For 39P/Oterma runs ($a_o = 7.25$ AU and $e_o = 0.25$), we obtained P_E equal to 1.2×10^{-6} and 2.5×10^{-6} for BULSTO and RMVS3 runs, respectively. These values are in accordance with the values of P_E obtained by Morbidelli *et al.* Morbidelli *et al.* (2000) considered reasonable that about $50 - 100m_\oplus$ of planetesimals primordially existed in the Jupiter-Saturn region and about $20 - 30m_\oplus$ of planetesimals in the Uranus-Neptune region. We think that they considerably underestimated the mass of planetesimals in the Uranus-Neptune region.

Lunine (2004, 2006) concluded that possible sources of water for Earth are diverse, and include Mars-sized hydrated bodies in the asteroid belt, smaller "asteroidal" bodies, water adsorbed into dry silicate grains in the nebula, and comets. Lunine *et al.* (2003) considered most of the Earth's water as a product of collisions between the growing Earth and planet-sized "embryos" from the asteroid belt. Drake & Campins (2006) noted that the key argument against an asteroidal source of Earth's water is that the O's isotopic composition of Earth's primitive upper mantle matches that of anhydrous ordinary chondrites, not hydrous carbonaceous chondrites. Kuchner *et al.* (2004) investigated the possibility that the Earth's ocean water originated as ice grains formed in a cold nebula, delivered to the Earth by drag forces from co-orbital nebular gas. Dust particles could also deliver water to the Earth from the feeding zone of the giant planets. Ipatov & Mather (2006a,b) obtained that the probability of collisions of $10 - 100 \mu\text{m}$ particles originated beyond Jupiter's orbit is about $(1 - 3) \times 10^{-4}$. Therefore the water in the terrestrial oceans ($2 \times 10^{-4}m_\oplus$) can be delivered by particles (for the model without sublimation) which had contained $\sim m_\oplus$ of water when they had been located beyond Jupiter. So dust particles could also play some role in the delivery of water to the terrestrial planets during planet formation.

There is the deuterium/hydrogen paradox of Earth's oceans (the D/H ratio is different for oceans and comets), but Pavlov *et al.* (1999) suggested that solar wind-implanted hydrogen on interplanetary dust particles provided the necessary low-D/H component of Earth's water inventory, and Delsemme (1999) considered that most of the seawater was brought by the comets that originated in Jupiter's zone, where steam from the inner solar system condensed onto icy interstellar grains before they accreted into larger bodies. It is likely (Drake & Campins 2006) that the D/H and Ar/O ratios measured in cometary comas and tails are not truly representative of cometary interiors.

Small bodies which collided with planets could deliver volatiles and organic/prebiotic compounds needed for life origin. Marov & Ipatov (2005) concluded that dust particles could be most efficient in the delivery of organic or even biogenic matter to the Earth, because they experience substantially weaker heating when passing through the atmosphere (an excess heat is radiated effectively due to high total surface-to-mass ratio

for dust particles). They assumed that life forms drastically different from the terrestrial analogs are unlikely to be found elsewhere in the solar system (if any), e.g., either extinct or extant life on Mars.

7. Conclusions

Some Jupiter-family comets can reach typical NEO orbits and remain there for millions of years. From the dynamical point of view (if comets didn't disintegrate) there could be (not 'must be') many (up to tens of percent) extinct comets among the NEOs, but, probably, many extinct comets disintegrated into mini-comets and dust during a smaller part of their dynamical lifetimes if these lifetimes were large. Disintegration of comets can provide a considerable fraction of cometary dust among the zodiacal dust particles. The probability of a collision of one object moving for a long time in Earth-crossing orbits, with the Earth could be greater than the sum of probabilities for thousands of other objects, even having similar initial orbits. Even without a contribution of such a few bodies, the probability of a collision of a former JFC (during its dynamical lifetime) with the Earth was greater than 4×10^{-6} . This probability is enough for delivery of all the water to Earth's oceans during formation of the giant planets. The ratios of probabilities of collisions of JFCs and HTC's with Venus and Mars to the mass of the planet usually were not smaller than that for Earth.

References

- Asher, D.J., Bailey, M.E. & Steel, D.I. 2001, in: M.Ya. Marov & H. Rickman (eds.), *Collisional Processes in the Solar System*, ASSL 261, 121
- Binzel, R.P., Xu, S., Bus, S.J. & Bowell, E. 1992, *Science* 257, 779
- Binzel, R.P., Lupishko, D. F., Di Martino, M., et al. 2002, in: W.F. Bottke Jr., A. Cellino, P. Paolicchi & R. P. Binzel (eds.), *Asteroids III* (Tucson: Univ. of Arizona), p. 255
- Binzel, R.P. & Lupishko, D.F. 2006, in: D. Lazzaro, S. Ferraz-Mello & J.A. Fernández (eds.), *Asteroids, Comets, and Meteors*, IAU Symposium 229 (Cambridge Univ. Press), p. 207
- Bottke, W.F., Morbidelli, A., Jedicke, R., Petit, J.-M., Levison, H.F., Michel, P. & Metcalfe, T.S. 2002, *Icarus* 156, 399
- Bottke, W.F., Vokrouhlický, D., Rubincam, D.P. & Nesvorný, D. 2006, *Annu. Rev. Earth Planet. Sci.* 34, 157
- Bulirsh, R. & Stoer, J. 1966, *Numer. Math.* 8, 1
- Chyba, C.F. 1989, *Nature* 343, 129
- Delsemme, A.H. 1999, *Planet. Space Sci.* 47, 125
- Drake, M. & Campins, H. 2006, in: D. Lazzaro, S. Ferraz-Mello & J.A. Fernández (eds.), *Asteroids, Comets, and Meteors*, IAU Symposium 229 (Cambridge Univ. Press), p. 381
- Duncan, M.J., Levison, H.F. & Budd, S.M. 1995, *Astron. J.* 110, 3073
- Farinella, P., Gonczi, R., Froeschlé, Ch. & Froeschlé, C. 1993, *Icarus* 101, 174
- Fernández, J.A. & Gallardo, T. 2002, *Icarus* 159, 358
- Fernández, Y.R., Jewitt, D.C. & Sheppard, S.S. 2001, *ApJ* 553, L197
- Frank, L.A., Sigwarth, J.B. & Graven, J.D. 1986a, *Geophys. Res. Lett.* 13, 303
- Frank, L.A., Sigwarth, J.B. & Graven, J.D. 1986b, *Geophys. Res. Lett.* 13, 307
- Harris, N.W. & Bailey, M.E. 1998, *Mon. Not. R. Astron. Soc.* 297, 1227
- Hsieh, H.H. & Jewitt, D. 2006, in: D. Lazzaro, S. Ferraz-Mello & J.A. Fernández (eds.), *Asteroids, Comets, and Meteors*, IAU Symposium 229 (Cambridge Univ. Press), p. 425
- Ipatov, S.I. 1987, *Earth, Moon, & Planets* 39, 101
- Ipatov, S.I. 1988, *Soviet Astron.* 32, 560
- Ipatov, S.I. 1993, *Solar Syst. Res.* 27, 65
- Ipatov, S.I. 1995, *Solar Syst. Res.* 29, 261
- Ipatov, S.I. 1999, *Celest. Mech. & Dyn. Astr.* 73, 107

- Ipatov, S.I. 2000, *Migration of celestial bodies in the solar system*, (Moscow: Editorial URSS Publishing Company) (in Russian)
- Ipatov, S.I. 2001, *Adv. Space Res.* 28, 1107
- Ipatov, S.I. 2002, in: B. Warmbein (ed.), *Asteroids, comets, meteors, 2002*, ESA SP-500, p. 371
- Ipatov, S.I. 2004, in: S.S. Holt & D. Deming (eds.), *The Search for Other Worlds*, AIP Conference Proceedings 713, p. 277
- Ipatov, S.I. & Hahn, G.J. 1999, *Solar Syst. Res.* 33, 487
- Ipatov S.I. & Mather J.C. 2003, *Earth, Moon, & Planets* 92, 89
- Ipatov, S.I. & Mather, J.C. 2004a, in: E. Belbruno, D. Folta & P. Gurfil (eds.), *Astrodynamics, Space Missions, and Chaos*, Annals New York Acad. Sci. 1017, p. 46
- Ipatov, S.I. & Mather, J.C. 2004b, *Adv. Space Res.* 33, 1524
- Ipatov, S.I. & Mather, J.C. 2006a, *Adv. Space Res.* 37, 126
- Ipatov, S.I. & Mather, J.C. 2006b, in: H. Kruger & A. Graps (eds.), *Dust in Planetary Systems*, in press, available from: <http://arXiv.org/format/astro-ph/0606434>
- Ipatov, S.I., Mather, J.C. & Taylor, P.A. 2004, in: E. Belbruno, D. Folta, & P. Gurfil (eds.), *Astrodynamics, Space Missions, and Chaos*, Annals New York Acad. Sci. 1017, 66
- Ipatov, S.I., Kutyrev, A.S., Madsen, G.J., Mather, J.C., Moseley, S.H. & Reynolds, R.J. 2006a, *37th LPSC*, #1471
- Ipatov, S.I., Kutyrev, A.S., Madsen, G.J., Mather, J.C., Moseley, S.H. & Reynolds, R.J. 2006b, *AJ*, submitted, available from: <http://arXiv.org/format/astro-ph/0608141>
- Jewitt, D. 2004, in: M.C. Festou, H.U. Keller & H.A. Weaver (eds.), *Comets II* (Tucson: Univ. Arizona Press), p. 659
- Jewitt, D. & Fernández, Y. 2001, in: M.Ya. Marov & H. Rickman (eds.), *Collisional Processes in the Solar System*, ASSL 261, p. 143
- Kuchner, M.J., Brown, M.E. & Holman, M. 2002, *Astron. J.* 124, 1221
- Kuchner, M.J., Youdin, A. & Bate, M. 2004, *Proc. of the Second TPF/Darwin Int. Conf.*, <http://planetquest1.jpl.nasa.gov/TPFDarwinConf/confProceedings.cfm>
- Levison, H.F. & Duncan, M.J. 1994, *Icarus* 108, 18
- Levison, H.F. & Duncan, M.J. 1997, *Icarus* 127, 13
- Levison, H.F., Dones, L., Chapman, C.R., et al. 2001, *Icarus* 151, 286
- Levison, H.F., Terrel, D., Wiegert, P.A., Dones, L. & Duncan, M.J. 2006, *Icarus* 182, 161
- Lunine, J.I. 2004, *Proc. of the Second TPF/Darwin International Conference*, <http://planetquest1.jpl.nasa.gov/TPFDarwinConf/confProceedings.cfm>
- Lunine, J.I., Chambers, J., Morbidelli, A. & Leshin, L.A. 2003, *Icarus* 165, 1
- Lunine, J.I. 2006, in: D.S. Lauretta & H.Y. McSween Jr. (eds.), *Meteorites and the Early Solar System II* (Tucson: Univ. Arizona Press), p. 309
- Lupishko, D.F. & Lupishko, T.A. 2001, *Solar Syst. Res.* 35, 227
- Marov, M.Ya. & Ipatov, S.I. 2001, in: M.Ya. Marov & H. Rickman (eds.), *Collisional Processes in the Solar System*, ASSL 261, p. 223
- Marov, M.Ya. & Ipatov, S.I. 2005, *Solar Syst. Res.* 39, 374
- Merline, W.J., Weidenschilling, S.J., Durda, D.D., Margot, J.-L., Pravec, P. & Storrs, A.D. 2002, in: W.F. Bottke Jr., A. Cellino, P. Paolicchi & R.P. Binzel (eds.), *Asteroids III* (Tucson: Univ. of Arizona), p. 289
- Morbidelli, A., Chambers, J., Lunine, J.I., Petit, J.-M., Robert, F., Valsecchi, G.B. & Cyr, K.E. 2000, *Meteorit. Planet. Sci.* 35, 1309
- Noll, K.S. 2006, in: D. Lazzaro, S. Ferraz-Mello & J.A. Fernández (eds.), *Asteroids, Comets, and Meteors*, IAU Symposium 229 (Cambridge Univ. Press), p. 301.
- Pavlov, A.A., Pavlov, A.K. & Kasting, J.F. 1999, *J. Geophys. Res.* 104, 30 725
- Pravec, P., Scheirich, P., Kusnirak, P., et al. 2006, *Icarus* 181, 63
- Rickman, H., Fernández, J.A., Tancredi, G. & Licandro, J. 2001, in: M.Ya. Marov & H. Rickman (eds.), *Collisional Processes in the Solar System*, ASSL 261, p. 131
- Weissman, P.R., Bottke, W.F. Jr. & Levison, H.F. 2002, in: W.F. Bottke Jr., A. Cellino, P. Paolicchi & R.P. Binzel (eds.), *Asteroids III* (Tucson: Univ. of Arizona), p. 669
- Wetherill, G.W. 1988, *Icarus* 76, 1