MIGRATION OF JUPITER-FAMILY COMETS AND RESONANT ASTEROIDS TO NEAR-EARTH SPACE

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ABSTRACT

We estimated the rate of comet and asteroid collisions with the terrestrial planets by calculating the orbits of 13000 Jupiter-crossing objects (JCOs) and 1300 resonant asteroids and computing the probabilities of collisions based on random-phase approximations and the orbital elements sampled with a 500 yr step. The Bulirsch-Stoer and a symplectic orbit integrator gave similar results for orbital evolution, but sometimes give different collision probabilities with the Sun. A small fraction of former JCOs reached orbits with aphelia inside Jupiter’s orbit, and some reached Apollo orbits with semi-major axes less than 2 AU, Aten orbits, and inner-Earth orbits (with aphelia less than 0.983 AU) and remained there for millions of years. Though less than 0.1% of the total, these objects were responsible for most of the collision probability of former JCOs with Earth and Venus. Some Jupiter-family comets can reach inclinations \(i > 90^\circ\). We conclude that a significant fraction of near-Earth objects could be extinct comets that came from the trans-Neptunian region.

INTRODUCTION

The main asteroid belt, the trans-Neptunian belt, and the Oort cloud are considered to be the main sources of the objects that could collide with the Earth. About 0.4% of the encounters within 0.2 AU of the Earth are from periodic comets (http://cfa-www.harvard.edu/iau/lists/CloseApp.html), and 6 out of 20 recent approaches of comets with the Earth within 0.102 AU were due to periodic comets (http://cfa-www.harvard.edu/iau/lists/ClosestComets.html). The fraction of close encounters with the Earth due to active comets is \(\sim 1\%\). Reviews of the asteroid and comet hazard were given by Ipatov (2000, 2001), and Bottke et al. (2002). Many scientists, e.g. Bottke et al. (2002), believe that asteroids are the main source of near-Earth objects (NEOs, i.e. objects with perihelion distance \(q < 1.3\) AU). However, Shoemaker et al. (1994) argued that active and extinct periodic comets may account altogether for about 20\% of the production of terrestrial impact craters larger than 20 km in diameter. There are about 40 active and 800 extinct Earth-crossing Jupiter-family comets with period \(P < 20\) yr and nuclei \(\geq 1\) km, and about 140–270 active Earth-crossing Halley-family comets (20 < \(P < 200\) yr).

Duncan et al. (1995) and Kuchner (2002) investigated the migration of trans-Neptunian objects (TNOs) to Neptune’s orbit, and Levison and Duncan (1997) studied the migration from Neptune’s orbit to Jupiter’s orbit. Ipatov and Hahn (1999) considered the migration of 48 Jupiter-crossing objects (JCOs) with initial orbits close to the orbit of Comet P/1996 R2 and found that on average such objects spend \(\sim 5000\) yr in orbits which cross both the orbits of Jupiter and Earth. Using these results and additional orbit integrations, and assuming that there are \(5 \times 10^9\) 1-km TNOs with \(30 < a < 50\) AU (Jewitt and Fernandez, 2001), Ipatov (2000, 2001) found that about \(10^4\) 1-km former TNOs are Jupiter-crossers now and 10-20\% or more 1-km
Earth-crossers could have come from the Edgeworth-Kuiper belt into Jupiter-crossing orbits. Note that previous estimates of the number of bodies with diameter \( d \geq 1 \) km and \( 30 \leq a \leq 50 \) AU were larger: \( 10^{10} \) (Jewitt et al., 1996) and \( 10^{11} \) (Jewitt, 1999). In the present paper we use the estimates by Ipatov (2001), but now include a much larger number of JCOs. Preliminary results were presented by Ipatov (2002, 2003a-b), who also discussed the formation of TNOs and asteroids.

**PROBABILITIES OF COLLISIONS OF NEAR-EARTH OBJECTS WITH PLANETS IN THE MODEL OF FIXED ORBITAL ELEMENTS**

As the actual collisions of migrating objects with terrestrial planets are rare, we use an approximation of random phases and orientations to estimate probabilities of collision for families of objects with similar orbital elements. We suppose that their semi-major axes \( a \), eccentricities \( e \) and inclinations \( i \) are fixed, but the orientations of the orbits can vary. When a minor body collides with a planet at a distance \( R \) from the Sun, the characteristic time to collide, \( T_f \), is a factor of \( k = v/v_c = \sqrt{2a/R(1-e)} \) times that computed with an approximation of constant velocity, where \( v \) is the velocity at the point where the orbit of the body crosses the orbit of the planet, and \( v_c \) is the velocity for the same semi-major axis and a circular orbit. This coefficient \( k \) modifies the formulas obtained by Ipatov (1988, 2000) for characteristic collision and close encounter times of two objects moving around the Sun in crossing orbits. These formulas also depend on the synodic period and improve on Opik’s formulas when the semi-major axes of the objects are close to each other. As an example, at \( e=0.7 \) and \( a=3.06 \) AU, we have \( k=2.26 \).

Based on these formulas, we calculated probabilities \( (1/T_f) \) for \( \sim 1300 \) NEOs, including 343 Venus-crossers, 756 Earth-crossers and 1197 Mars-crossers. The values of \( T_f \) (in Myr), \( k \), and the number \( N_f \) of objects considered are presented in Table 1. We considered separately the Atens, Apollos, Amors, and several Jupiter-family comets (JFCs). The relatively small values of \( T_f \) for Atens and for all NEOs colliding with the Earth are due to several Atens with small inclinations discovered during the last three years. If we increase the inclination of the Aten object 2000 SG344 from \( i=0.1^\circ \) to \( i=1^\circ \), then for collisions with the Earth we find \( T=28 \) Myr and \( k=0.84 \) for Atens and \( T=97 \) Myr and \( k=1.09 \) for NEOs. These times are much longer, and illustrate the importance of rare objects.

| Planet | Atens \( T_f \) | Apollos \( k \) | Amors \( N_f \) | NEOs \( T_f \) | JFCs \( T_f \) |
|--------|----------------|----------------|----------------|----------------|----------------|
| Venus  | 106 1.2 94 | 186 1.7 248 | – | 154 1.5 343 | 2900 2.5 |
| Earth  | 15 0.9 110 | 164 1.4 643 | 211 2.0 1 | 67 1.1 756 | 2200 2.3 |
| Mars   | 475 0.4 6 | 4250 0.9 574 | 5810 1.1 616 | 4710 1.0 1197 | 17000 1.8 |

**ORBITAL EVOLUTION OF JUPITER-FAMILY COMETS AND RESONANT ASTEROIDS**

As the next step in estimating probabilities, we calculated the orbits for thousands of test particles with orbits similar to known comets and asteroids, but having slightly different initial conditions. The results confirm that most of the collision probability comes from a handful of very rare cases in which the test particle is Earth-crossing for an extended period of time. They also show that the initial conditions matter more than the choice of orbit integrator.

For initial investigations of the migration of bodies under the gravitational influence of the planets, we used the integration package of Levison and Duncan, 1994. In most cases we omitted the influence of Mercury and Pluto. Here and in Tables 2-3 and Figs. 1, 2a-c, 3-5 we present the results obtained by the Bulirsh-Stoer method (BULSTO code; Bulirsh and Stoer, 1966) with the integration step error less than \( \varepsilon \in [10^{-9},10^{-8}] \), and in the next section we compare them with those of BULSTO with \( \varepsilon \leq 10^{-12} \) and a symplectic method.

In the first series of runs (denoted as \( n1 \)) we calculated the evolution of 1900 JCOs moving in initial
orbits close to those of 20 real JCOs with period \(5 < P_a < 9 \) yr. In other series of runs, initial orbits were close to those of a single comet (2P, 9P, 10P, 22P, 28P, or 39P). For the 2P runs, we included Mercury in the integrations. We also investigated the orbital evolution of asteroids initially moving in the 3:1 and 5:2 resonances with Jupiter. For the JCOs we varied only the initial mean anomaly \( \nu \). The number of objects in one run usually was \( \leq 250 \). In most JCO cases the time \( \tau \) when perihelion was passed was varied with a step \( d\tau \leq 1 \) day (i.e., \( \nu \) was varied with a step \(<0.2^\circ\) ). Near the \( \tau \) estimated from observations, we used smaller steps. In most JCO cases the range of initial values of \( \tau \) was less than several tens of days. For asteroids, we varied initial values of \( \nu \) and the longitude of the ascending node from 0 to 360°. The approximate values of initial orbital elements are presented in Table 2. We initially integrated the orbits for \( T_S \geq 10 \) Myr. After 10 Myr we tested whether some of remaining objects could reach inside Jupiter’s orbit; if so, the calculations were usually continued. Therefore the results for orbits crossing or inside Jupiter’s orbit were the same as if the integrations had been carried to the entire lifetimes of the objects. For Comet 2P and resonant asteroids, we integrated until all objects were ejected into hyperbolic orbits or collided with the Sun. In some previous publications we have used smaller \( T_S \), so these new data are more accurate.

In our runs, planets were considered as material points so literal collisions did not occur. However, using the formulas of the previous section, and the orbital elements sampled with a 500 yr step, we calculated the mean probability \( P \) of collisions. We define \( P \) as \( P_T/N \), where \( P_T \) is the probability for all \( N \) objects of a collision of an object with a planet during its lifetime, the mean time \( T = T_S/N \) during which perihelion distance \( q \) of an object was less than the semi-major axis \( a_{pl} \) of the planet, and the mean time \( T_f \) during which an object moved in Jupiter-crossing orbits. The values of \( P_T=10^6 P_f \) and \( T_f \) are shown in Table 2. Here \( r \) is the ratio of the total time interval when orbits are of Apollo type (\( a>1 \) AU, \( q=a(1-e)<1.017 \) AU) at \( e<0.999 \) to that of Amor type (1.017<\( q<1.3 \) AU) and \( T_c/T_f \) (in Gyr). In almost all runs \( T \) was equal to the mean time in planet-crossing orbits and \( 1/T_c \) was a probability of a collision per year (similar to \( 1/T_f \)). The results showed that most of the probability of collisions of former JCOs with the terrestrial planets is due to a small \((\sim 0.1-1\%) \) fraction that orbited for several Myr with aphelion \( Q<4.7 \) AU. Some had typical asteroidal and NEO orbits and reached \( Q<3 \) AU for several Myr. Time variations in orbital elements of JCOs obtained by the BULSTO code are presented in Figs. 1, 2a-b. Plots in Fig. 1 are more typical than those in Fig. 2a-b, which were obtained for two JCOs with the highest probabilities of collisions.

| \( N \) | \( a \) | \( e \) | \( i \) | \( P_T \) | \( T \) | \( T_c \) | \( T_f \) | \( T_c/T_f \) | \( P_T=10^6 P_f \) | \( T_f \) |
|---|---|---|---|---|---|---|---|---|---|---|
| 2P | 501 | 0.22 | 0.85 | 12° | 141 | 345 | 2.45 | 110 | 397 | 3.61 |
| 28P | 1000 | 0.54 | 4.7° | 1.44 | 2.98 | 2.07 | 1.76 | 4.87 | 2.77 | 0.74 |
| 39P | 750 | 0.75 | 0.25 | 1.9° | 1.06 | 1.72 | 1.62 | 1.19 | 3.03 | 2.55 |
| \( \Sigma \) | 7349 | 9.52 | 16.2 | 1.70 | 12.6 | 27.9 | 2.21 | 4.89 | 62.4 | 12.8 |
| \( \Sigma \) | 7850 | 17.9 | 37.7 | 2.11 | 18.8 | 51.5 | 2.74 | 5.29 | 85.9 | 16.2 |
| \( \Sigma \) | 7852 | 130. | 72.6 | 0.56 | 84.5 | 95.7 | 1.13 | 13.5 | 132.4 | 9.81 |
| R2 | 24 | 3.79 | 0.31 | 2.6° | 0.53 | 0.6 | 1.13 | 2.84 | 1.6 | 0.56 |
| 3 : 1 | 288 | 2.5 | 0.15 | 10° | 1286 | 1886 | 1.47 | 1889 | 2747 | 1.45 |
| 5 : 2 | 288 | 2.82 | 0.15 | 10° | 101 | 173 | 1.71 | 318 | 371 | 1.16 |

Table 2. Mean probability \( P=10^{-6} P_f \) of a collision of an object with a planet (Venus=V, Earth=E, Mars=M) during its lifetime, mean time \( T \) (in Kyr) during which \( q<a_{pl} \), \( T_c=T/P \) (in Gyr), mean time \( T_f \) (in Kyr) spent in Jupiter-crossing orbits, and ratio \( r \) of times spent in Apollo and Amor orbits. Results from BULSTO code with \( \varepsilon \sim 10^{-9}-10^{-8} \). For \( N=7349 \), 2P runs were excluded.
with the terrestrial planets. Fig. 2c shows the plots for an asteroid from the 3:1 resonance with Jupiter. The results obtained by a symplectic code for two JCOs are presented in Fig. 2d-e. Large values of $P$ for Mars in the $n1$ runs were caused by a single object with a lifetime of 26 Myr.

Total times spent by $N$ JCOs and asteroids during their lifetimes in orbits typical for inner-Earth objects (IEOs, $Q<0.983$ AU), Aten ($a<1$ AU and $Q>0.983$ AU), Al2 ($q<1.017$ AU and $1<a<2$ AU), Apollo, and Amor objects are presented in Table 3. These times for Earth-crossing objects were mainly due to a few tens of objects with high collision probabilities. Of the JCOs with initial orbits close to those of 10P and 2P, six and nine respectively moved into Apollo orbits with $a<2$ AU (Al2 orbits) for at least 0.5 Myr each, and five of them remained in such orbits for more than 5 Myr each. The contribution of all the other objects to Al2 orbits was smaller. Only one and two JCOs reached IEO and Aten orbits, respectively.

Table 3. Times (in Myr) spent by $N$ JCOs and asteroids during their lifetimes, with results for first 50 Myr in [ ]

|       | N | IEOs | Aten | Al2 | Apollo | Amor | $a > 5$ AU |
|-------|---|------|------|-----|--------|------|-------------|
| JCOs  | 7852 | 10   | 86   | 411 | 659    | 171  | 7100        |
| JCOs without 2P | 7350 | 10   | 3.45 | 23  | 207    | 145  | 7000        |
| 3 : 1 | 288 | 13   | 4.5  | 433 | [190]  | [790] | [540]       |
| 5 : 2 | 288 | 0    | 0    | 17  | [2]    | [113] | [90]        |

One former JCO (Fig. 2a), which had an initial orbit close to that of 10P, moved in Aten orbits for 3.45 Myr, and the probability of its collision with the Earth from such orbits was 0.344 (so $T_c=10$ Myr was even smaller than the values of $T_f$ presented in Table 1; i.e., this object had smaller $e$ and $i$ than typical observed Atens), greater than that for the 7850 other simulated former JCOs during their lifetimes (0.15). It also moved for about 10 Myr in inner-Earth orbits before its collision with Venus, and during this time the probability $P_V=0.655$ of its collision with Venus was greater ($P_V \approx 3$ for the time interval presented in Fig. 2a) than that for the 7850 JCOs during their lifetimes (0.14). At $t=0.12$ Myr orbital elements of this object jumped considerably and the Tisserand parameter increased from $J<3$ to $J>6$, and $J>10$ during most of its lifetime. Another object (Fig. 2b) 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. These two objects were not included in Table 2 except for the entry for $N=7852$. Ipatov (1995) obtained the migration of JCOs into IEO and Aten orbits using the approximate method of spheres of action for taking into account the gravitational interactions of bodies with planets. The mean time $T_E$ during which a JCO was moving in Earth-crossing orbits is $9.6 \times 10^4$ yr for the 7850 simulated JCOs, and $\approx 8 \times 10^3$ yr for the $n1$ case. The data for Comet P/1996 R2 (line R2) were not included in the sums in Table 2. In the present paper we consider only the integration into the future. Ipatov and Hahn (1999) integrated the evolution of Comet P/1996 R2 both into the future and into the past, in this case $T_E = 5 \times 10^3$ yr. The ratio $P_S$ of the number of objects colliding with the Sun to the total number of escaped (collided or ejected) objects was less than 0.015 for the considered runs (except for 2P).

| Series | $n1$ | 9P | 10P | 22P | 28P | 39P |
|--------|------|----|-----|-----|-----|-----|
| $P_S$  | 0.0005 | 0  | 0.014 | 0.002 | 0.007 | 0 |

Some former JCOs spent a long time in the 3:1 resonance with Jupiter (Fig. 1a-b) and with $2<a<2.6$ AU. Other objects reached Mars-crossing orbits for long times. We conclude that JCOs can supply bodies to the regions which are considered by many scientists (Bottke et al., 2002) to belong to the main sources of NEOs, and that those rare objects that make transitions to typical NEO orbits dominate the statistics. Only computations with very large numbers of objects can hope to reach accurate conclusions on collision probabilities with the terrestrial planets.
Fig. 1. Time variations in $a$, $e$, $q$, $Q$, $\sin(i)$ for a former JCO in initial orbit close to that of Comet 10P (a-f), or Comet 2P (g-h). Results from BULSTO code with $\varepsilon \sim 10^{-9} - 10^{-8}$. 
Fig. 2. Time variations in $a$, $e$, $q$, $Q$, and $i$ for a former JCO in initial orbit close to that of Comet 10P (a), 2P (b, e), 9P (d), or an asteroid at the 3/1 resonance with Jupiter (c). For (a) at $t<0.123$ Myr $Q>a > 1.5$ AU. Results from BULSTO code with $\varepsilon \sim 10^{-9} - 10^{-8}$ (a-c) and by a symplectic method with $d_s=30$ days (d) and with $d_s=10$ days (e).
In Fig. 3 we present the time in Myr during which objects had semi-major axes in an interval with a width of 0.005 AU (Figs. 3a-b) or 0.1 AU (Figs. 3c-d). At 3.3 AU (the 2:1 resonance with Jupiter) there is a gap for asteroids that migrated from the 5:2 resonance and for former JCOs (except 2P).

For the n1 data set, $T_J = 0.12$ Myr and, while moving in Jupiter-crossing orbits, objects had orbital periods $P_a < 10$, $10 < P_a < 20$, $20 < P_a < 50$, $50 < P_a < 200$ yr for 11%, 21%, 21%, and 17% of $T_J$, respectively. Therefore, there are three times as many JCOs as Jupiter-family comets (for which $P_a < 20$ yr). We also found that some JCOs, after residing in orbits with aphelia deep inside Jupiter’s orbit, transfer for tens of Myr to the trans-Neptunian region, either in low or high eccentricity orbits. We conclude that some of the main belt asteroids may reach typical TNO orbits, and then become scattered-disk objects having high eccentricities, and vice versa. The fraction of objects from the 5:2 resonance that collided with the Earth was only 1/6 of that for the 3:1 resonance. Only a small fraction of the asteroids from the 5:2 resonance reached $a < 2$ AU (Fig. 3b).

The distributions of migrating former JCOs and resonant asteroids in $a$ and $e$ (left) and in $a$ and $i$ (right) are presented in Fig. 4-5. For each picture we considered 250 migrating objects (288 for Fig. 5), 100 intervals for $a$, and about the same number of intervals for $e$ and $i$. Different designations correspond to different numbers $n$ of orbital elements (calculated with a step of 500 yr) in one bin (in Fig. 4 ‘$<=$’ means $\leq$). All the former JCOs reached low eccentricity orbits very rarely with $2 < a < 3.5$ AU and $11 < a < 28$ AU. There were many positions of objects when their perihelia were close to a semi-major axis of a giant planet, mainly of Jupiter (Fig. 4a). Note that Ozernoy et al. (2000) considered the migration of Neptune-crossers and found that the main concentrations of perihelia were near Neptune’s orbit. The pictures are different for different runs. For initial orbits close to that of Comet 2P, orbits often reached $90^\circ < i < 180^\circ$ with various values of $a > 1.7$ AU (Fig. 4c). For Fig. 4b (Comet 10P) the values $90^\circ < i < 120^\circ$ were obtained only at $2.4 < a < 3$ AU.

COMPARISON OF ORBIT INTEGRATORS

To determine the effect of the choice of orbit integrators and convergence criteria, we made additional runs with BULSTO at $\varepsilon = 10^{-13}$ and $\varepsilon = 10^{-12}$ and with a symplectic integrator. The orbital evolution of 5400 JCOs was computed with the RMVS3 code. For the symplectic method we used an integration step $d_s$ of 3, 10, and 30 days. We find that the results are not the same. On the other hand, the differences between integrator choices (with $d_s \leq 10$ days) are comparable to the differences between runs with slightly different initial conditions. Our interpretation is that 1) very small numbers of particles contribute most of the collision probabilities with the terrestrial planets, 2) runs with larger numbers of particles are more reliable, and 3) small differences in initial conditions or in the errors of the orbit integrators modify the trajectories substantially, especially for those particles making major changes in their orbits due to close encounters or resonances. We conclude that for the purposes of this paper, the various choices of orbit integrator are sufficiently equivalent.

To illustrate these points, Tables 4-5 present the results obtained by BULSTO with $\varepsilon \leq 10^{-12}$ and the symplectic method with $d_s \leq 10$ days. Most of the results obtained with these values of $\varepsilon$ and $d_s$ are statistically similar to those obtained for $10^{-9} \leq \varepsilon \leq 10^{-8}$. For example, a few objects spent millions of years in Earth-crossing orbits inside Jupiter’s orbit (Figs. 1-2), and their probabilities of collisions with the Earth were thousands of times greater than for more typical objects. For series n1 the probability of a collision with Earth for one object with initial orbit close to that of Comet 46P was 88.3% of the total probability for 1200 objects from this series, and the total probability for 1198 objects was only 4%. This object and the object presented in Fig. 2e and in the first line of Table 4 were not included in Table 5 with $N = 1199$ for n1 and with $N = 250$ for 2P, respectively. For the 3:1 resonance with $d_s = 10$ days, 142 objects spent 140 and 84.5 Myr in IEO and Aten orbits, respectively, even longer than for $\varepsilon \sim 10^{-9} - 10^{-8}$. Additionally, up to 40 Myr and 20 Myr were spent in such orbits by two other objects which had estimated probabilities of collisions with the terrestrial planets greater than 1. For the 2P runs with $\varepsilon \leq 10^{-12}$ and $N = 100$, the calculated objects spent 5.4 Myr in Apollo orbits with $a < 2$ AU.

The values of $P_r$ presented in Table 5 are usually of the same order of magnitude as those in Table 2, and the difference between the data presented in these tables is comparable to the differences between different runs belonging to a series. For Earth and Venus, the values of $P_r$ presented in both tables are about 1–4 for
Fig. 3. Distribution of migrating JCOs (a, c-d) and resonant asteroids (b) with their semi-major axes. The curves plotted in (c) at \(a=40\) AU are (top-to-bottom) for sum, 10P, n1, 39P, 22P, 9P, 28P, and 2P. For Figs. (a) and (c), designations are the same. Results from BULSTO code with \(\varepsilon \sim 10^{-9} - 10^{-8}\).
Fig. 4. Distribution of migrating objects in semi-major axes, eccentricities, and inclinations for objects in initial orbits close to that of 10P (a-b), 2P (c), and 39P (d). BULSTO code with $\varepsilon \sim 10^{-9} - 10^{-8}$. 
Table 4. Times (Myr) spent by three objects in various orbits, and probabilities of collisions with Venus ($p_v$), Earth ($p_e$), and Mars ($p_m$) during their lifetimes $T_{lt}$ (in Myr)

| $d_s$ or $\varepsilon$ | IEOs | Aten | Al2  | Apollo | Amor | $T_{lt}$ | $p_v$ | $p_e$ | $p_m$ |
|------------------------|------|------|------|--------|------|----------|------|------|------|
| 2P                     | $10^4$ | 12 | 33.6 | 73.4  | 75.6 | 4.7 | 126 | 0.18 | 0.68 | 0.07 |
| 46P                    | $10^4$ | 0  | 0    | 11.7  | 14.2 | 4.2 | 19.5 | 0.02 | 0.04 | 0.002 |
| resonance 3 : 1        | $10^{-12}$ | 0  | 0    | 20    | 233.5 | 10.4 | 247 | 0.008 | 0.013 | 0.0007 |

9P, 22P, 28P and 39P. For 28P and 39P with the symplectic method $P_r$ is about twice that for BULSTO. For 10P they are several times larger than for the above series, and for 2P they are several times larger than for 10P. For the n1 run, $P_r>4$ for Earth. The ratio of $P_r$ to the mass of the planet was typically several times larger for Mars than for Earth and Venus. The main difference in $P_r$ was found for the 3:1 resonance. In this case greater values of $P_r$ were obtained for $d_s=10$ days. As noted above, a few exceptional objects dominated the probabilities, and for the 3:1 resonance two objects, which had collision probabilities greater than unity for the terrestrial planets, were not included in Table 5. These two objects can increase the total value of $P_r$ for Earth by a factor of several.

We also did some symplectic runs with $d_s=30$ days. For most of the objects we got similar results, but about 0.1% of the objects reached Earth-crossing orbits with $a<2$ AU for several tens of Myr (e.g., Fig. 2d) and even IEO orbits. These few bodies increased the mean value of $P$ by a factor of more than 10. With $d_s=30$ days, four objects from the runs n1, 9P, 10P had a probability of collisions with the terrestrial planets greater than 1 for each, and for 2P there were 21 such objects among 251 considered. For resonant asteroids, we also obtained much larger values than those for BULSTO for $P_r$ and $T$ for RMVS3 with $d_s=30$ days, and similarly for the 3:1 resonance even with $d_s=10$ days. For this resonance it may be better to use $d_s<10$ days. Probably, the results of symplectic runs with $d_s=30$ days can be considered as such migration that includes some nongravitational forces.

In the case of close encounters with the Sun (Comet 2P and resonant asteroids), the probability $P_S$ of collisions with the Sun during lifetimes of objects was larger for RMVS3 than for BULSTO, and for $10^{-13} \leq \varepsilon \leq 10^{-12}$ it was greater than for $10^{-9} \leq \varepsilon \leq 10^{-8}$ ($P_S=0.75$ for the 3:1 resonance with $d_s=3$ days). This probability is presented in Table 6 for several runs.

For Comet 2P the values of $T_J$ were much smaller for RMVS3 than those for BULSTO and they were smaller for smaller $\varepsilon$; for other runs these values do not depend much on the method. In our opinion, the most reliable values of $P_S$ and $T_J$ were obtained with $10^{-13} \leq \varepsilon \leq 10^{-12}$. In the direct integrations reported
Table 5. Probabilities of collisions with the terrestrial planets. Designations are same as those for Table 2. Results from the BULSTO code with $\varepsilon \leq 10^{-12}$ and a symplectic method with $d_s \leq 10$ days.

| $\varepsilon$ or $d_s$ | N  | $P_r$ | $T_r$ | $T_c$ | $P_r$ | $T_r$ | $T_c$ | $r$ | $T_J$ |
|------------------------|----|-------|-------|-------|-------|-------|-------|-----|-------|
| $n1$                   | 1200 | 25.4 | 13.8  | 0.54  | 40.1  | 24.0  | 0.60  | 2.48 | 35.2  | 14.2 | 3.0  | 117 |
| $10^d$                 | 1199 | 7.88  | 9.70  | 1.23  | 4.76  | 12.6  | 2.65  | 0.76 | 16.8  | 22.1 | 2.8  | 117 |
| $10^{-12}$             | 100  | 321   | 541   | 1.69  | 146   | 609   | 4.2   | 14.8 | 634   | 42.8 | 27.0 | 20  |
| $P$                    | 251  | 860   | 570   | 0.66  | 2800  | 788   | 0.28  | 294  | 825   | 2.81 | 22.0 | 0.29 |
| $P$                    | 250  | 160   | 297   | 1.86  | 94.2  | 313   | 3.32  | 10.0 | 324   | 32.3 | 35.1 | 0.29 |
| $P$                    | 400  | 1.37  | 3.46  | 2.53  | 3.26  | 7.84  | 2.40  | 1.62 | 23.8  | 14.7 | 1.1  | 128 |
| $P$                    | 450  | 14.9  | 30.4  | 2.04  | 22.4  | 41.3  | 1.84  | 6.42 | 113.0  | 17.6 | 1.5  | 85  |
| $P$                    | 250  | 0.68  | 2.87  | 4.23  | 1.39  | 4.96  | 3.57  | 0.60 | 11.5  | 19.2 | 1.5  | 121 |
| $P$                    | 250  | 3.87  | 35.3  | 9.12  | 3.99  | 59.0  | 14.8  | 0.71 | 109.0  | 15.4 | 2.2  | 535 |
| $P$                    | 250  | 2.30  | 2.68  | 1.17  | 2.50  | 4.22  | 1.69  | 0.45 | 7.34  | 16.3 | 2.2  | 92  |
| $3:1$                  | 70   | 1.162 | 1943  | 1.67  | 1511  | 5901  | 3.91  | 587  | 803   | 1.37 | 4.6  | 326 |
| $3:1$                  | 142  | 27700 | 8617  | 0.31  | 2725  | 9177  | 3.37  | 1136 | 9939  | 8.749 | 16.4 | 1244 |
| $5:2$                  | 50   | 130   | 113   | 0.87  | 168   | 230   | 1.37  | 46.2 | 507   | 11.0 | 1.4  | 166 |
| $5:2$                  | 144  | 58.6  | 86.8  | 1.48  | 86.7  | 174   | 2.01  | 17.0 | 354.8 | 20.9 | 1.73 | 224 |

Table 6. Probability of collisions with the Sun

| $\varepsilon = 10^{-13}$ | $\varepsilon = 10^{-12}$ | $\varepsilon = 10^{-9}$ | $\varepsilon = 10^{-8}$ | $d_s = 10$ days | $d_s = 30$ days |
|--------------------------|--------------------------|--------------------------|--------------------------|-----------------|-----------------|
| Comet 2P                 | 0.88                     | 0.88                     | 0.38                     | 0.32            | 0.99            | 0.8            |
| resonance 3:1            | 0.46                     | 0.5                      | 0.156                    | 0.112           | 0.741           | 0.50           |
| resonance 5:2            | 0.06                     | 0.062                    | 0.028                    | 0.099           | 0.155           |                |

by Valsecchi et al. (1995), 13 of the 21 objects fell into the Sun, so their value of $P_S=0.62$ is in accordance with our results obtained by BULSTO; it is less than that for $\varepsilon = 10^{-12}$, but greater than for $\varepsilon = 10^{-9}$. Note that even for different $P_S$ the data presented in Tables 2 and 5 usually are similar. As we did not calculate collision probabilities of objects with planets by direct integrations, but instead calculated them with the random phase approximation from the orbital elements, we need not make integrations with extremely high accuracy. Ipatov (1988b) showed that for BULSTO the integrals of motion were conserved better and the plots of orbital elements for closely separated values of $\varepsilon$ were closer to one another with $10^{-9} \leq \varepsilon \leq 10^{-8}$. The smaller the value of $\varepsilon$, the more integrations steps are required, so $\varepsilon \leq 10^{-12}$ for large time intervals are not necessarily better than those for $10^{-9} \leq \varepsilon \leq 10^{-8}$. Small $\varepsilon$ is clearly necessary for close encounters. Ipatov and Hahn (1999) and Ipatov (2000) found that former JCOs reached resonances more often for BULSTO than for RMVS3 with $d_s=30$ days. Therefore we made most of our BULSTO runs with $10^{-9} \leq \varepsilon \leq 10^{-8}$. For a symplectic method it is better to use smaller $d_s$ at a smaller distance $R$ from the Sun, but in some runs $R$ can vary considerably during the evolution.

MIGRATION FROM BEYOND JUPITER TO THE TERRESTRIAL PLANETS

According to Duncan et al. (1995), the fraction $P_{TNJ}$ of TNOs reaching Jupiter’s orbit under the influence of the giant planets in 1 Gyr is 0.8-1.7%. As the mutual gravitational influence of TNOs can play a larger role in variations of their orbital elements than collisions (Ipatov, 2001), we considered the upper value of $P_{TNJ}$. Using the total of $5 \times 10^9$ 1-km TNOs with $30 < a < 50$ AU, and assuming that the mean time for a body to move in a Jupiter-crossing orbit is 0.12 Myr, we find 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 7350 (not including our 2P runs) and 7852 simulated JCOs in various orbits, we obtain the following numbers of 1-km former TNOs now moving in several types of orbits:

| \( N \) | IEOs | Aten | Al2 | Apollo | Amor |
|------|------|------|-----|--------|------|
| 7350 | 120  | 40   | 250 | 2500   | 1750 |
| 7852 | 110  | 950  | 4500| 7200   | 1880 |

For example, the number of IEOs \( N_{IEO} = N_J t_{IEO}/(N_J t_J) \), 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. As we considered mainly the runs with relatively high migration to the Earth, the actual above values are smaller by a factor of several, the actual portion of IEOs and Atens can be smaller and that for Amors can be larger than those for our runs. Even if the number of Apollo objects is an order of magnitude smaller than the above value, it may still be comparable to the real number (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 values of the characteristic time (usually \( T_e \)) for the collision of a former JCO or a resonant asteroid with a planet (see Tables 2 and 5) are greater than the values of \( T_f \) for NEOs in Table 1, \( T_e \approx 1.1 \text{ Gyr} \) for 7852 objects, so we expect that the mean inclinations and eccentricities of unobserved NEOs are greater than those for the NEOs that are already known. Jedecke et al., (2003) found similar results. On average, the values of \( T_e \) for our \( n1 \) series and for most of our simulated JCOs were not greater than those for our calculated asteroids, and migrating Earth-crossing objects had similar \( e \) and \( i \) for both former JCOs and resonant asteroids (see e.g. Fig. 4-5). Former JCOs, which move in Earth-crossing orbits for more than 1 Myr, while moving in such orbits, usually had larger \( P \) and smaller \( e \) and \( i \) (sometimes similar to those of the observed NEOs, see Figs. 1-2). It is easier to observe orbits with smaller values of \( e \) and \( i \), and probably, many of the NEOs moving in orbits with large values of \( e \) and \( i \) have not yet been discovered. About 1% of the observed Apollos cross Jupiter’s orbit, and an additional 1% of Apollos have aphelia between 4.7-4.8 AU, but these Jupiter-crossers are far from the Earth most of time, so their actual fraction of ECOs is greater than for observed ECOs. The fraction of Earth-crossers among observed Jupiter-family comets is about 10%. This is a little more than \( T/T_f \) for our \( n1 \) runs, but less than for 7850 JCOs. For our former resonant asteroids, \( T_f \) is relatively large (\( \approx 0.2 \text{ Myr} \)), and such asteroids can reach cometary orbits.

Comets are estimated to be active for \( \sim 10^8-10^9 \) yr. 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 is about 0.4 Myr. This time corresponds to 40-400 extinct comets of this type. Note that the diameter of Comet 2P Encke is about 5-10 km, so the number of smaller extinct comets can be much larger.

The above estimates of the number of NEOs are approximate. For example, it is possible that the number of 1-km TNOs is several times smaller than \( 5 \times 10^9 \), while some scientists estimated that this number can be up to \( 10^{11} \). Also, the fraction of TNOs that have migrated towards the Earth might be smaller. On the other hand, the above number of TNOs was estimated for \( a<50 \) AU, and TNOs from more distant regions can also migrate inward. The Oort cloud could also supply Jupiter-family comets. According to Asher et al. (2001), the rate of a cometary object decoupling from the Jupiter vicinity and transferring to an NEO-like orbit is increased by a factor of 4 or 5 due to nongravitational effects (see also Fernandez and Gallardo, 2002). This would result in larger values of \( P_e \) and \( T \) than those shown in Tables 2 and 5. Our estimates show that, in principle, the trans-Neptunian belt can provide a significant portion of the Earth-crossing objects, although many NEOs clearly came from the main asteroid belt. It may be possible to explore former TNOs near the Earth’s orbit without sending spacecraft to the trans-Neptunian region.

More than half of the close encounters of active comets with the Earth belong to long-period comets, which amount to about 80% of the known population. Thus, though probabilities are smaller for larger eccentricities, the number of collisions of both long-period and short-period active comets with the inner planets can be of the same order of magnitude. According to our results, many former Jupiter-family comets can have orbits typical of asteroids, and collide with the Earth from typical NEO orbits.
Based on the estimated collision probability \( P = 4 \times 10^{-6} \) we find that 1-km former TNOs now collide with the Earth once in 0.75 Myr. This value of \( P \) is smaller than that for our \( n_1 \) runs, and is only 1/20 of that for our 7852 JCOs. Assuming the total mass of planetesimals that ever crossed Jupiter’s orbit is \( \sim 100 m_\oplus \), where \( m_\oplus \) is the mass of the Earth (Ipatov, 1993, 2000), we conclude that the total mass of bodies that impacted the Earth is \( 4 \times 10^{-4} m_\oplus \). If ices comprised only half of this mass, then the total mass of ices \( M_{\text{ice}} \) that were delivered to the Earth from the feeding zone of the giant planets is about the mass of the terrestrial oceans \( \sim 2 \times 10^{-4} m_\oplus \).

The calculated probabilities of collisions of objects with planets show that the fraction of the mass of the planet delivered by short-period comets can be greater for Mars and Venus than for the Earth (compare the values of \( P/m_{pl} \) using \( P \) from Tables 2 and 5). This larger mass fraction would result in relatively large ancient oceans on Mars and Venus. On the other hand, there is the deuterium/hydrogen paradox of Earth’s oceans, as the D/H ratio is different for oceans and comets. Pavlov et al. (1999) suggested that solar wind-implanted hydrogen on interplanetary dust particles could provide the necessary low-D/H component of Earth’s water inventory.

Our estimate of the migration of water to the early Earth is in accordance with Chyba (1989), but is greater than those of Morbidelli et al. (2000) and Levison et al. (2001). The latter obtained smaller values of \( M_{\text{ice}} \), and we suspect that this is because they did not take into account the migration of bodies into orbits with \( Q<4.5 \) AU. Perhaps this was because they modeled a relatively small number of objects, and Levison et al. (2001) did not take into account the influence of the terrestrial planets. In our runs the probability of a collision of a single object with a terrestrial planet could be much greater than the total probability of thousands of other objects, so the statistics are dominated by rare occurrences that might not appear in smaller simulations. The mean probabilities of collisions can differ by orders of magnitude for different JCOs. Other scientists considered other initial objects and smaller numbers of Jupiter-crossing objects, and did not find decoupling from Jupiter, which is a rare event. We believe there is no contradiction between our present results and the smaller migration of former JCOs to the near-Earth space that was obtained in earlier work, including our own papers (e.g. Ipatov and Hahn, 1999), where we used the same integration package.

There is additional evidence from the classification of objects based on their albedos. From measured albedos, Fernandez et al. (2001) concluded that the fraction of extinct comets among NEOs and unusual asteroids is significant (at least 9% are candidates). The idea that there may be many extinct comets among NEOs was considered by several scientists. Rickman et al. (2001) believed that comets played an important and perhaps even dominant role among all km-size Earth impactors. In their opinion, dark spectral classes that might include the ex-comets are severely underrepresented (see also Jewitt and Fernandez, 2001). Our runs showed that if one observes former comets in NEO orbits, then it is probable that they have already moved in such orbits for millions (or at least hundreds of thousands) years, and only a few of them have been in such orbits for short times (a few thousand 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 (some of these encounters can be very close to the Sun, e.g. in the case of Comet 2P at \( t>0.05 \) Myr), could have lost their mantles, which causes their low albedo, and so change their albedo and would look like typical asteroids. Typical comets have larger rotation periods than typical NEOs (Binzel et al., 1992, Lupishko and Lupishko, 2001), but, while losing considerable portions of their masses, extinct comets can decrease these periods. In future we plan to consider a larger initial number of objects initially located beyond Jupiter in order to better estimate their probabilities of migration to a near-Earth space.

CONCLUSIONS

Collision statistics for the terrestrial planets are dominated by very small numbers of bodies that reach orbits with high collision probabilities, so it is essential to consider very large numbers of particles. The initial conditions for the orbit integrations appear to matter more than the choice of orbit integrator. Some Jupiter-family comets can reach typical NEO orbits and remain there for millions of years. While the probability of such events is small (about 0.1% in our runs and perhaps smaller for other initial data), nevertheless the majority of collisions of former JCOs with the terrestrial planets are due to such objects. The amount of water delivered to the Earth during planet formation could be about the mass of the Earth.
oceans. From the dynamical point of view there could be (not ‘must be’) many extinct comets among the NEOs. For better estimates of the portion of extinct comets among NEOs we will need orbit integrations for many more TNOs and JCOs, and wider analysis of observations and craters.

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