Migration of icy objects to forming terrestrial planets

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Introduction

The problem of the delivery of water to the terrestrial planets was studied by several scientists.

(a) Endogenous sources of water could include:

=Adsorption of water on to grains before the gas in the inner solar system was dissipated (Drake & Campins, 2006; Muralidharan et al., 2008). **Water storage potential in minerals in the silicate Earth is about several (**5-6, **up to 50) Earth oceans**, and it is likely that Mars, Earth, and Venus all accreted some water by adsorption of water on to grains before the gas in the inner solar system was dissipated, with Mars accreting the most both**.** Hallis et al. (2015) noted that **the deep mantle water has a low D/H ratio** and could be acquired due to adsorption of water on fractal grains during Earth's accretion. **The ocean water (and its D/H ratio) could be a result of mixing of water from several sources,** e.g., **with high and low D/H ratios.**

Another andogenous source of water is direct adsorption of hydrogen from nebular gas into magma oceans (reaction of H_2 with FeO = water; the increase of D/H ratio in Earth oceans by a factor of 2-9) (Genda & Icoma, 2008).

Introduction

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(a) Exogenous sources of water:

= The outer asteroid belt. O'Brien et al. (2014), Morbidelli et al. (2000), Petit et al. (2001), Raymond et al. (2004) and Lunine et al. (2003, 2007).

Drake and Campins (Proc. IAU Symp. N 229, 2006, 381-394) noted that **the key argument against an asteroidal source of Earth's water as the main source of water is that the Os (osmium) isotopic composition of Earth's primitive upper mantle matches that of anhydrous ordinary chondrites, not hydrous carbonaceous chondrites.**

= Another exogenous source of water are planetesimals and comets from beyond Jupiter's orbit.
Morbidelli et al. (2000), Levison et al. (2001). For the Grand Tack model, Rubie et al. (2015) considered migration from the region 6-9.5 AU.

Drake and Campins (Proc. IAU Symp. N 229, 2006, 381-394) supposed that cometary contribution of water to the Earth does not exceed 50%. There are also smaller estimates of the fraction of cometary water, because the D/H ratio for most of comets is greater than that for the Earth. For Comet 103P/Hartley 2, the D/H ratio $(1.61 \pm 0.24)\times10^{-4}$ is close to that of the Earth.

Our computer simulations

Our previous studies [e.g., Marov & Ipatov (2001, 2005), Ipatov (2000, 2001, 2010), Ipatov & Mather (2003, 2004, 2006, 2007)] **of the delivery of water and volatiles to the terrestrial planets were based on our computer simulations of the orbital evolution of several tens of thousands of small bodies and dust particles which orbits were close to orbits of discovered comets.**

Recently we studied migration of planetesimals from the feeding zone of Jupiter and Saturn not only to the present terrestrial planets, but also to their embryos. In our new runs, as in our previous runs, **the gravitational influence of considered planets was taken into account. The symplectic method was used for integration.**

If most of the amount of water, equaled to at least several Earth oceans, was from endogenous sources, then the cometary contribution of water of up to the mass of Earth oceans could affect not much on the D/H ratio of all Earth's water.

Besides, the composition (e.g., **D/H ratio) of planetesimals in the feeding zone of the giant planets**, especially in the feeding zone of Jupiter and Saturn, **could differ from the data obtained at observations of some comets.**

Series of our recent calculations

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In series JS, **we considered the present orbits and masses of the terrestrial planets, Jupiter and Saturn**.

It is considered in several cosmogonic models that Jupiter and Saturn have been almost formed when masses of forming terrestrial planets were far from the present masses. Therefore, **in series JS_{01}**, **masses of planets in the terrestrial zone were smaller by a factor of ten than masses of the present terrestrial planets.**

In series JN and JN_{01}, in addition to the initial data for series JS and JS_{01}, **we also considered present Uranus and Neptune.**

In these four series, **semi-major axes *a* of initial orbits of planetesimals varied from a_{min}=4.5 to a_{max}=12 AU**, and the number of planetesimals with semi-major axis *a* was proportional to $a^{1/2}$. (For Grand Tack model, a_{min}=6 AU. In this case, migration to the Earth is a little smaller).

Initial eccentricities and inclinations of planetesimals were equal to 0.3 and 0.15 rad, respectively. **Such eccentricities could be reached due to gravitational influence of planetesimals and planets** (Ipatov, 1993, 2000).

Calculations of the characteristic time elapsed up to the encounter of two objects to radius of sphere

Based on obtained arrays of orbital elements of planetesimals during their dynamical lifetimes (until their ejections into hyperbolic orbits or collisions with planets or the Sun), **we calculated the probabilities of collisions of migrating planetesimals with planets.**

$$T_2 = 6.28 \cdot k_p \cdot T_s \cdot R \cdot k_v / (r_s \cdot k_{fi}) \text{ - planar model,}$$

$$T_3 = T_2 \cdot \Delta i \cdot R / r_s \text{ - spatial motel;}$$

R is the distance of encounter from the Sun, k_{fi} is the sum of angles (in radians) with apices in the Sun, within which the distance between orbits is less than r_s, T_s is the synodic period of revolution, $k_p = P_2/P_1$, where $P_2 > P_1$, P_i is a period of revolution of the i-th body around the Sun.

In order to take into account that velocity at distance R from the Sun differs from the mean velocity, we used coefficient $k_v = \mathrm{sqrt}\{2a/R-1\}$.

In contrast to the approach used by Opik (1951) and Arnold (1965), T depends on orbital orientations and on a synodic period.

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Results of computer simulations

For series JS, JS_{01}, JN and JN_{01}, the probabilities of collisions of a planetesimal with the terrestrial planets during its dynamical lifetime are presented in Tables.

***Table 1*. The probability of a collision of a planetesimal from the feeding zone of Jupiter and Saturn with a considered terrestrial planet.**

	Mercury	Venus	Earth	Mars
JS	**1.58×10^{-7}**	**2.05×10^{-6}**	**2.02×10^{-6}**	**4.35×10^{-7}**
JN	**0.92×10^{-7}**	**1.15×10^{-6}**	**1.92×10^{-6}**	**7.2×10^{-7}**

***Table 2*. The probability of a collision of a planetesimal from the feeding zone of Jupiter and Saturn with a considered terrestrial planet divided by mass of the planet relative to that of the Earth.**

	Mercury	Venus	Earth	Mars
JS	**1.4**	**1.24**	**1.0**	**2.0**
JN	**0.87**	**0.73**	**1.0**	**3.5**

***Table 3*. The probabilities p_E and p_{E01} of a collision of a planetesimal from the feeding zone of Jupiter and Saturn with a planet in the Earth's orbit at a mass of the planet equal to m_E and $0.1m_E$, respectively. $\lg p=\lg(p_{E01}/p_E)$**

	JS	JS_{01}	JN	JN_{01}
p_E	**2.02×10^{-6}**	1.83×10^{-6}	**1.92×10^{-6}**	1.11×10^{-6}
p_{E01}	3.66×10^{-7}	**3.63×10^{-7}**	3.68×10^{-7}	**1.99×10^{-7}**
$\lg p$	**0.74**	**0.70**	**0.72**	**0.746**

Probability of a collision of a planetesimal with the Earth

In series JS and JN, for consideration of several thousands of planetesimals, **the probability p_E of a collision of a planetesimal with the Earth was about 2×10^{-6}. It is smaller than the value of $\geq4\times10^{-6}$ obtained in our previous calculations for initial bodies in Jupiter-crossing cometary orbits, because not all planetesimals became Jupiter-crossers.**

For the Grand Tack model, the region from 3 to 6 AU is considered free from planetesimals due to the accretion of Jupiter and Saturn which migrated inwards towards the Sun and then outwards from the Sun (Rubie et al. 2015).

The probabilities of collisions of planetesimals with the terrestrial planets will be a little lower if we consider the inner border of the disk equal to 6 AU, but not to 4.5 AU.

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Probability of a collision of a planetesimal with the terrestrial planets and their embryos

In series JS_{01}, the probability p_{E01} of a collision of a planetesimal with the Earth embryo of mass $0.1m_E$ was obtained to be equal to 4×10^{-7}.

In the series JS, JS_{01}, JN and JN_{01}, the fraction of planetesimals that reached the orbit of the Earth during evolution was about 12–14%.

We also made calculations **for the series of runs for which the giant planets of present masses initially were located more close to each other than the present giant planets.** The values of p_E **and** p_{E01} **for such runs were usually not smaller than the values for the series** JS, JS_{01}, JN and JN_{01} (**in which giant planets were in their present orbit**s). **For** such **runs with close giant planets, at least one giant planet** (not Jupiter) **was ejected into a hyperbolic orbit during evolution**. **Note that it is considered** based on microlensing observations **that there are nearly two free-floating planets for every star.**

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The total mass of water delivered to the Earth

• **At $p_E=2\times10^{-6}$, for the total mass of planetesimals in the feeding zone of Jupiter and Saturn to be about a hundred of Earth masses** [Ipatov S.I. (1993) Solar System Research, 27, 65-79]**, and at the fraction of water in planetesimals equal to 0.5, one can obtain that about a half of the mass of water in Earth's oceans could be delivered from this zone.**

• **About the same amount of water could be delivered to the Earth from distances greater than 12 AU.** The main delivery from such greater distances could be later than from the feeding zone of Jupiter and Saturn, and could take place when the Earth was almost formed.

• **Consideration of mutual gravitational influence of planetesimals would increase their eccentricities, and so the amount of planetesimals collided with the terrestrial planets.**

• At smaller values of the fraction of water in planetesimals and of the total mass of planetesimals, the amount of delivered water is smaller than the above estimates.

• **Our computer simulations testify in favor of that the total mass of water delivered to the Earth from the region beyond Jupiter's orbit could be up to the mass of water in Earth's oceans.**

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Planetesimals and water delivered to Mars, Venus, and Mercury

In series JS, the ratio of the probability of a collision of a planetesimal with a planet to the mass of the planet was greater by about a factor of 2, 1.2 and 1.4 for Mars, Venus and Mercury, respectively, than that for the Earth. For series JN, these ratios are 3.5, 0.7 and 0.9.

Based on our studies, we concluded**:**

The amount of water delivered to Venus and Mercury per mass of a planet could be similar to that delivered to the Earth.

The amount of water delivered to Mars was only by a factor of 3 or 5 smaller than that delivered to the Earth, and **the amount per mass of a planet was greater for Mars than for Earth by a factor of 2 or 3.**

These estimates testify in favor of ancient oceans on Mars and Venus.

Probabilities of collisions of planetesimals with growing Earth

Based on our calculations, **we can conclude that at the growth of the mass of the Earth embryo up to 0.5m_E, the mass of water delivered to the Earth could be about 30% of all water delivered to the Earth from the feeding zone of Jupiter and Saturn.**

These estimates show that a considerable fraction of water could be delivered to the embryo of the Earth when its mass was smaller than the present mass of the Earth.

For the Grand Tack model, most water (originated from beyond 6-7 AU, bodies contained 20% water ice) was added to the Earth mainly after 60-80% of its final mass has accreted (Rubie et al. 2015).

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Planetesimals and water delivered to the Moon

Orbits of Earth-crossing objects that migrated from outside Jupiter's orbit are typically highly eccentric. For such eccentric orbits, the effective radii of the Earth and the Moon are approximately proportional to their radii. The square of the ratio of radii of the Earth and the Moon is 13.48.

Based on our runs of migration of planetesimals from the feeding zone of Jupiter and Saturn and of migration of Jupiter-crossing objects, **we calculated probabilities of collisions of such planetesimals and objects with the Moon. Such probabilities were typically smaller than probabilities of collisions with the Earth by a factor of 16 or 17 for planetesimals and many Jupiter-family comets.** However, in some runs for Jupiter-family comets the factor was up to 25.

The amount of the material, including water, delivered to the Moon from outside Jupiter's orbit could be smaller by about a factor of 20 than that delivered to the Earth.

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Motion of JCOs in NEO orbits for a long time

The orbital evolution of >30,000 bodies with initial orbits close to those of Jupiter-family **comets** (JFCs), Halley-type comets, long-period comets**,** and asteroids in the resonances 3/1 and 5/2 with Jupiter***, and also of >20,000* dust particles *produced by these small bodies was integrated*** a few years ago. Gravitational influence of 7 planets (Venus-Neptune) was taken into account. For dust particles, we also consider radiation pressure, Poynting-Robertson drag and solar wind drag.

Methods of integration. We used the SWIFT package by Levison and Duncan (Icarus, 1994, v. 108, 18-36). ***Bulirsh-Stoer method (BULSTO)*** with the error per integration step less than $\varepsilon=10^{-9}$, or $\varepsilon=10^{-8}$, or some value between these two values. Also $\varepsilon=10^{-12}$ and $\varepsilon=10^{-13}$ were used. ***A symplectic method*** with an integration step $3\le d_s\le 10$, or $d_s=30$ days (RMVS3). **Both methods gave similar results.**

The considered time interval in one run usually was equal to the largest dynamical lifetime of bodies in the run (***until all bodies reached 2000 AU or collided with the Sun***). Sometimes it reached several hundreds Myr.

Among 30000 Jupiter-crossing objects (JCOs), a few JCOs got orbits located inside Jupiter's orbit and moved in such orbits for millions or even hundreds of millions of years. The probability of a collision of such object with a terrestrial planet can be greater than the total probability of thousands of other JCOs.

Actually, comets split into mini-comets and dust during many **millions of years.**

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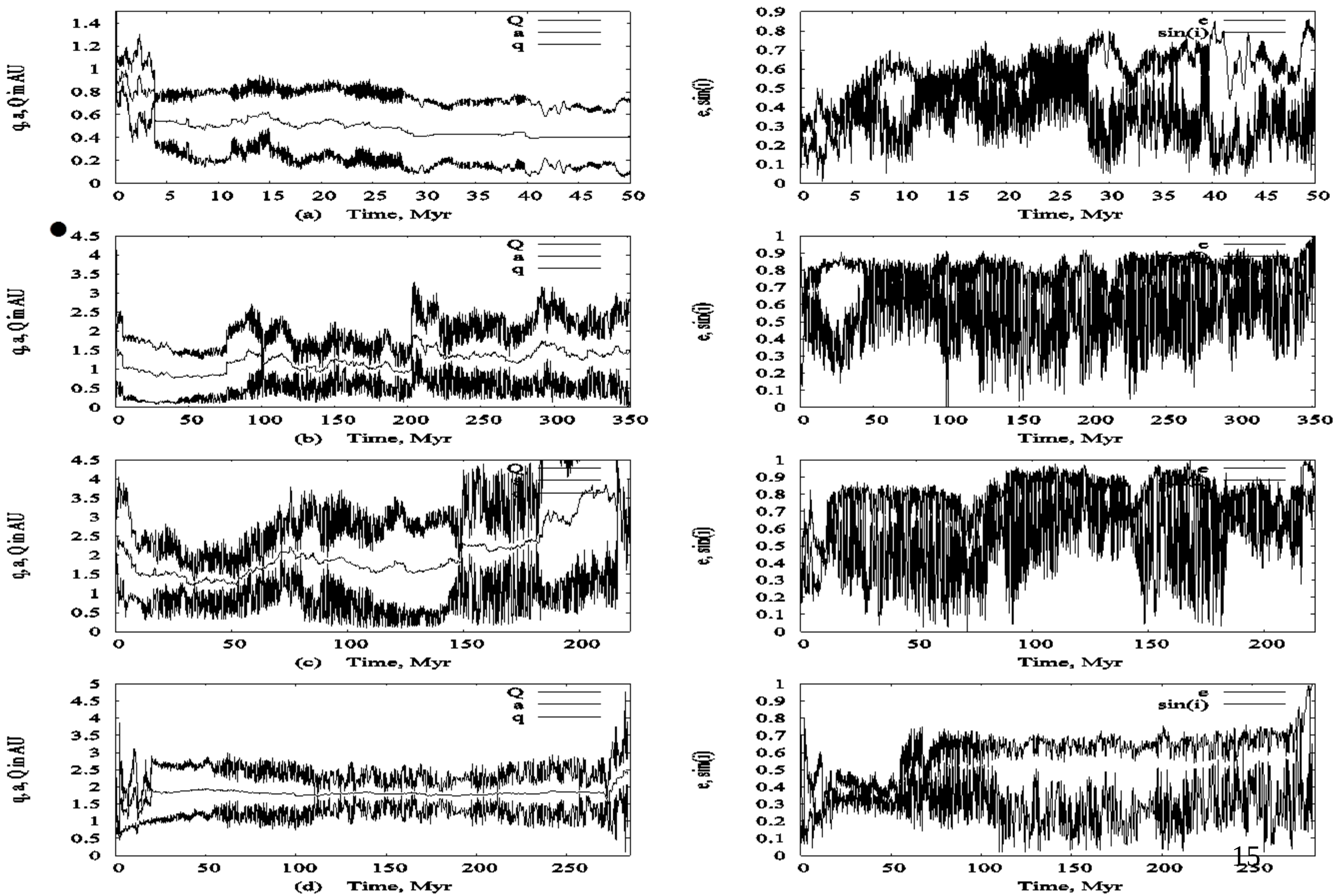
Time variations in semi-major axis (left), eccentricity and sin*i* (right)

for objects moved for a long time inside Jupiter's orbit

10P (a, d), 2P (b), resonance 3:1 ©. BULSTO (a-c), RMVS (d)



Probabilities $P=10^{-6}P_r$ of collisions of bodies with the terrestrial planets

			V	**V**	**E**	**E**	**E**	**M**	**M**	**-**	
	ε, d_s	N	$\boldsymbol{P_r}$	T_r	$\boldsymbol{P_r}$	T_r	T_c	$\boldsymbol{P_r}$	T	r	T_d
n1	**10^{-9}**	**1900**	**2.4**	**4.2**	**4.5**	**7.9**	**1760**	**6.1**	**30.0**	**0.7**	**20**
n1	**10^{d}**	**1200**	**25.4**	**13.8**	**40.1**	**24.0**	**600**	**2.48**	**35.2**	**3.0**	**25.7**
n1	**10^{d}**	**1199***	**7.88**	**9.70**	**4.76**	**12.6**	**2650**	**0.76**	**16.8**	**2.8**	**10.3**
n2	**10^{-9}**	**4000**	**9.9**	**24.4**	**11.6**	**35.6**	**3060**	**2.12**	**56.3**	**2.7**	**7.7**
n2	**10^{d}**	**10000**	**14.7**	**24.8**	**14.9**	**36.1**	**2420**	**2.88**	**56.1**	**3.1**	**90.1**
2P	**10^{-9}**	*501**	*141*	*345*	***110***	*397*	*3610*	*10.5*	*430*	*18.*	*249*
9P	**10^{-9}**	800	1.3	1.8	3.7	4.1	1100	0.7	9.7	1.2	2.6
10P	**10^{-9}**	*2149**	*28.3*	*41.3*	*35.6*	*71*	*1970*	*10.3*	*16.4*	*1.6*	*107*
22P	**10^{-9}**	1000	1.44	2.98	1.76	4.87	2770	0.74	11.0	1.6	1.5
28P	**10^{-9}**	750	1.7	21.8	1.9	34.7	18260	0.44	68.9	1.9	0.1
39P	**10^{-9}**	*750*	*1.06*	*1.72*	***1.19***	*3.03*	*2550*	*0.31*	*6.82*	*1.6*	*2.7*
44P	**10^{-9}**	*500*	*2.58*	*15.8*	*4.01*	*24.9*	*6210*	*0.75*	*46.3*	*2.0*	*8.6*
3:1	**10^{-9}**	288	1286	1886	1889	2747	1450	488	4173	2.7	5169
5:2	**10^{-9}**	288	101	173	318	371	1160	209	1455	0.5	1634

T_r (the mean time in a planet-crossing orbit) and T_d are in Kyr, $T_c=T_r/P_r$ in Myr, $\boldsymbol{P_r}=10^6 P_\Sigma/N$ for Venus=**V**, Earth=**E**, Mars=**M.** T_d is the mean time spent in orbits with $Q=a(1+e)<4.2$ AU. r is the ratio of times spent in Apollo and Amor orbits. For one object (from 10P runs), its probability of collisions with Earth and Venus was **0.3 and 0.7**, respectively. For another object (from 2P runs) during its lifetime (352 Myr), its probability of collisions with Earth, Venus and Mars was **0.172, 0.224, and 0.065**, respectively. For 12,000 other objects with BULSTO such probability was **0.2, 0.18, and 0.04**, respectively. Results with the BULSTO code at $10^{-9}\le\varepsilon\le10^{-8}$ are marked as 10^{-9}, those at $\varepsilon\le10^{-12}$ are marked as 10^{-12}, and those with the RMVS3 code are at integration step d_s. For the lines which do not include all bodies in a series of runs, the number of objects N is marked by *. **Mean probabilities of collisions with the Earth exceeded $4\cdot10^{-6}$, but mean probabilities for different cometary orbits can differ by up two orders of magninute, and the probability for one object could be greater than that for thousands objects in almost the same orbits.**

Conclusions on migration JCOs and TNOs to the Earth

- The calculations for material points testify in favor of that the number of *former TNOs now moving in Earth-crossing orbits can be about 2/3 of the estimated number of Earth-crossers with d>1 km* (750).

•**Results of these runs testify** in favor of at least one of these conclusions:

•1) **the fraction of 1-km former trans-Neptunian objects (TNOs) among near-Earth objects (NEOs) can exceed several tens of percents, if TNOs are considered as material points**,

•2) the number of TNOs migrating inside solar system could be smaller by a factor of several than it was earlier considered,

•3) **it is more probable that 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.

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Probabilities of collisions of migrating dust particles with the Earth

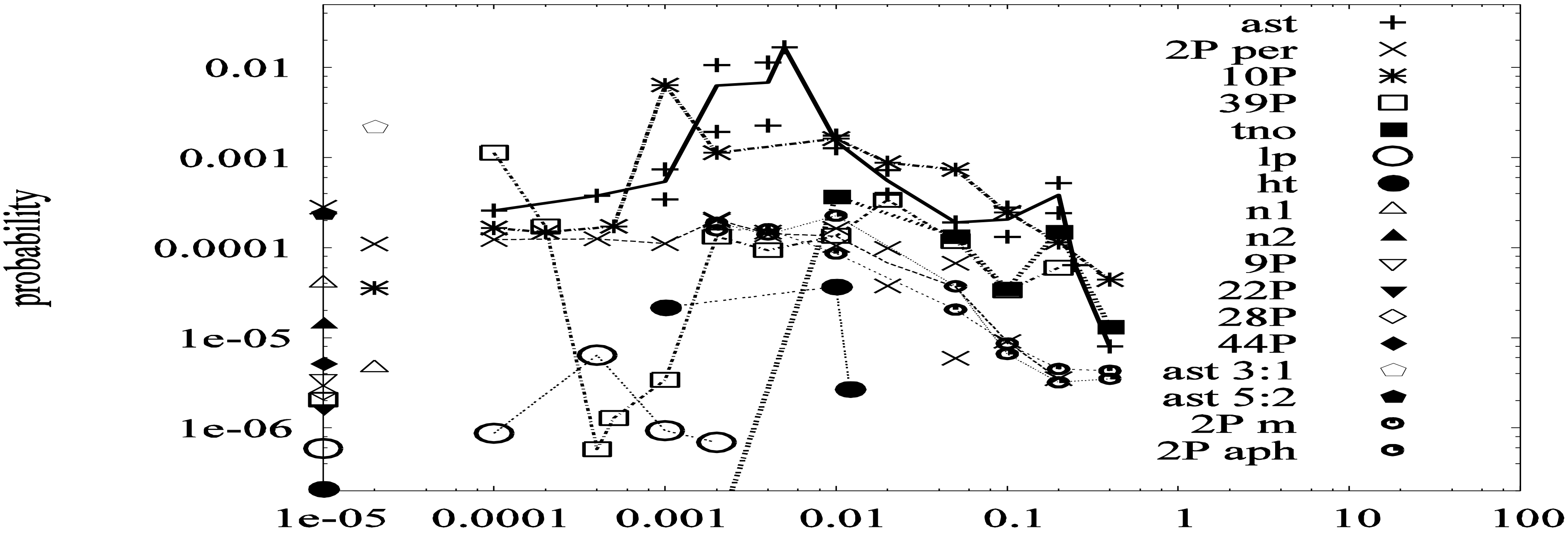


Fig. 1. The probability *P* of collisions of dust particles and bodies (during their dynamical lifetimes) with the Earth **versus β (the ratio between the radiation pressure force and the gravitational force)** for particles launched from asteroids (ast), trans-Neptunian objects (tno), and different comets.

For dust particles produced by comets and asteroids, **the probability P_E of a collision with the Earth was found to have a maximum** (~0.001-0.005) **at 0.002≤β≤0.01, i.e., at *d*~100 μm** (**микрон**, this value of *d* is in accordance with observational data).

These maximum values of P_E were usually (exclusive for Comet 2P) greater at least by an order of magnitude than the values for parent comets. **Dust particles could be more effective than bodies in delivery of organic material to the Earth because of smaller heating during the motion in atmosphere.**

Probabilities of collisions of migrating dust particles with Venus and Mars

Probabilities of collisions of considered dust particles with Venus were of the same order as those for Earth, and those for Mars were about an order of magnitude smaller.

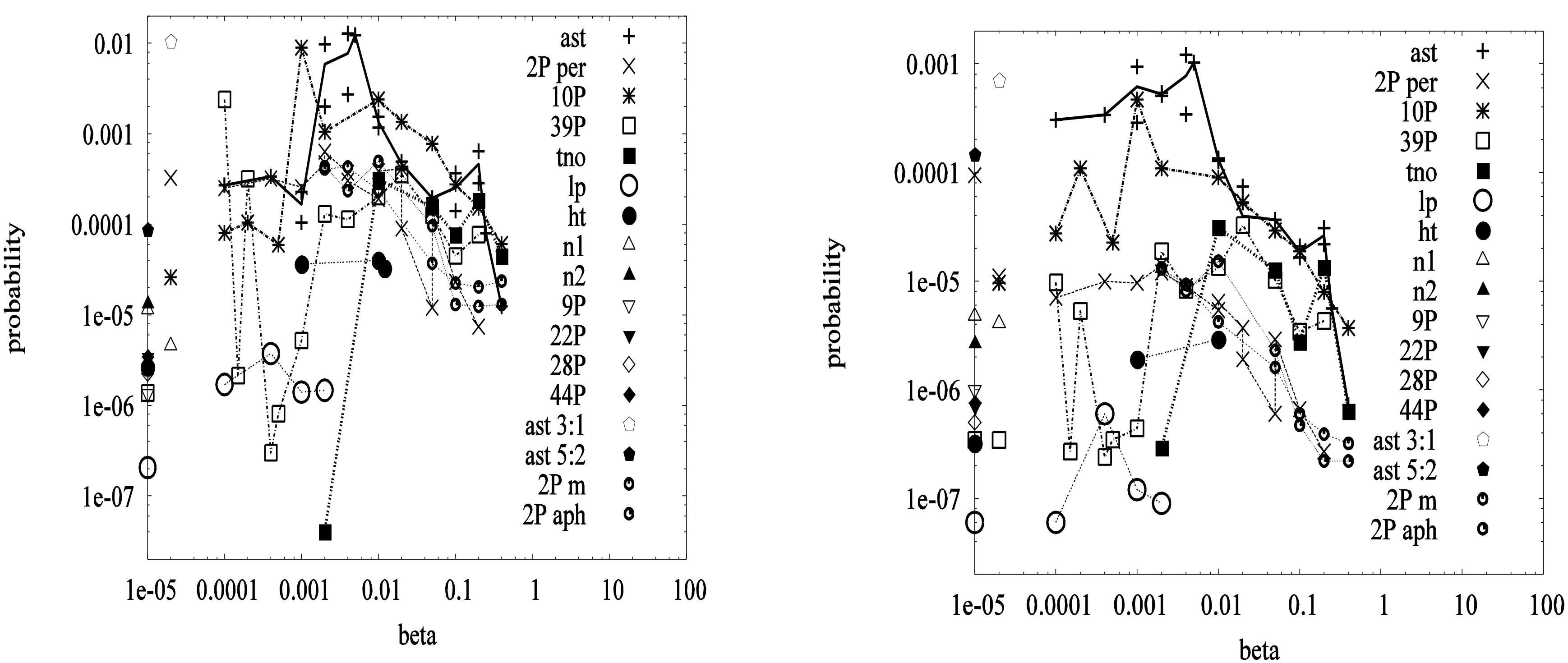


Fig. 2. The probability *P* of collisions of dust particles and bodies (during their dynamical lifetimes) with **Venus (left) and Mars (right)** versus β (the ratio between the radiation pressure force and the gravitational force). Designations are the same as those for Fig. 1.

Probabilities of collisions of migrating dust particles with Mercury

Depending on a source of dust, probabilities of collisions of considered dust particles with Mercury can be smaller or greater than those for Mars.

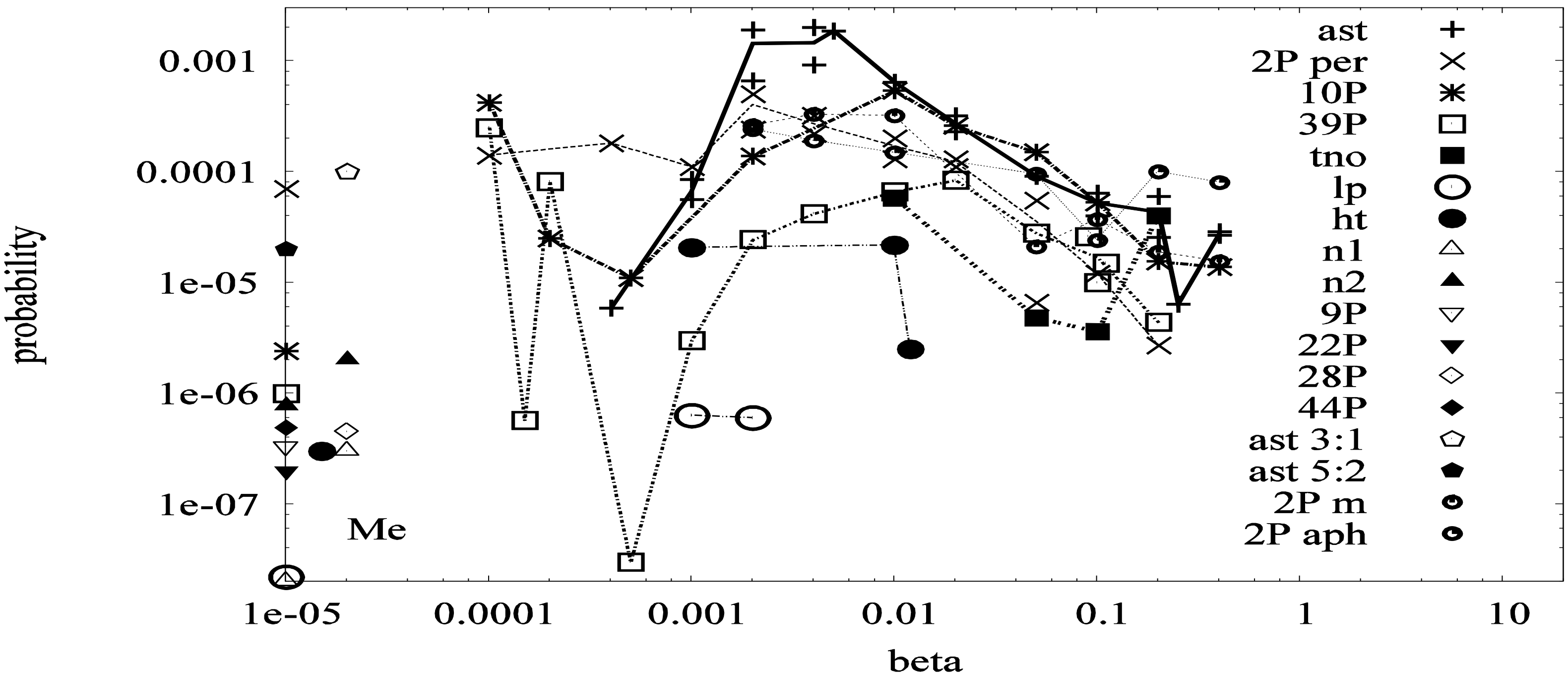
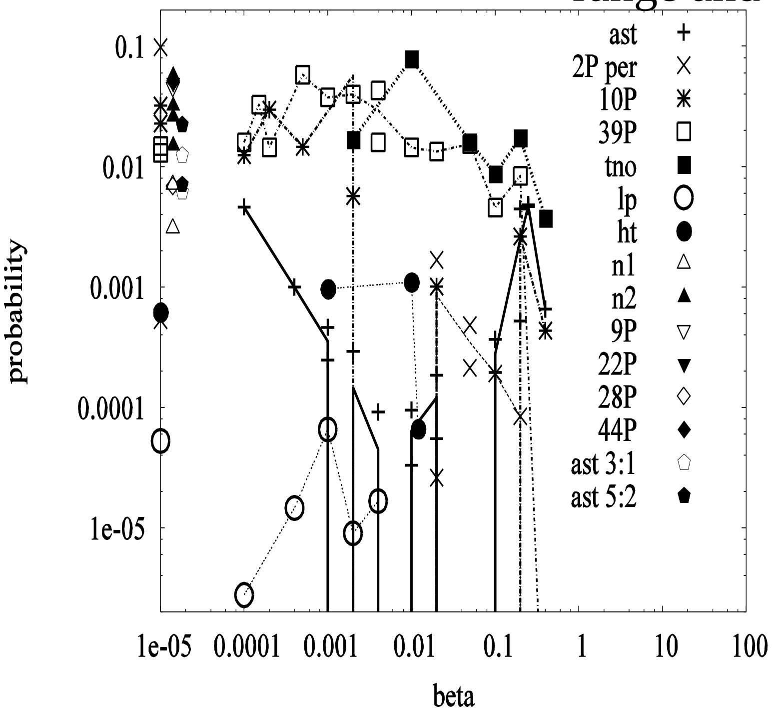


Fig. 3. The probability *P* of collisions of dust particles and bodies (during their dynamical lifetimes) with Mercury versus β (the ratio between the radiation pressure force and the gravitational force). Designations are the same as those for Fig. 1.

Probabilities of collisions of migrating dust particles with Jupiter and Saturn

Probabilities of collisions of considered dust particles and bodies with Jupiter during their dynamical lifetimes are smaller than 0.1. They can ***reach 0.01-0.1 for bodies and particles initially moved beyond Jupiter's orbit***. For bodies and dust particles initially moved inside Jupiter's orbit, the probabilities are usually smaller than the above range and can be equal to zero.



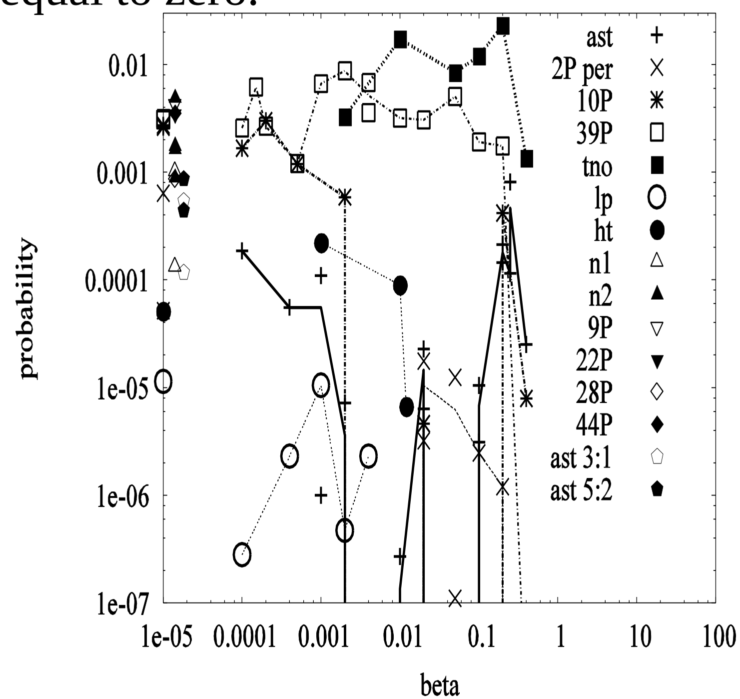


Fig. 4. The probability *P* of collisions of dust particles and bodies (during their dynamical lifetimes) with **Jupiter (left) and Saturn (right**) versus β (the ratio between the radiation pressure force and the gravitational force). Designations are the same as those for Fig. 1.

Probabilities of collisions of migrating dust particles with Uranus and Neptune

Probabilities of collisions of migrating dust particles (exclusive for trans-Neptunian particles) with other giant planets **were usually smaller than those with Jupiter**.

The total probability of collisions of any typical considered body or particle with all planets didn’t exceed 0.2.

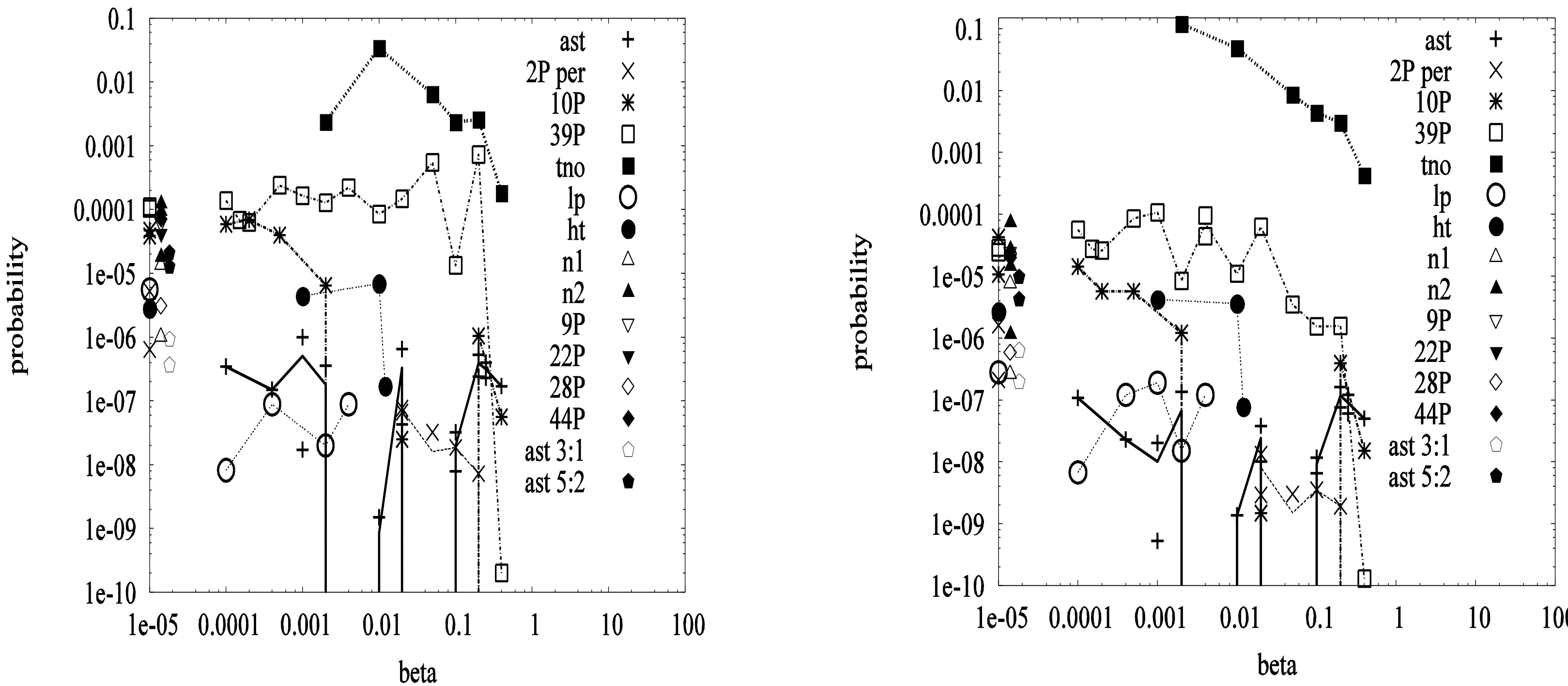


Fig. 5. The probability *P* of collisions of dust particles and bodies (during their dynamical lifetimes) with Uranus (left) and Neptune (right) versus β (the ratio between the radiation pressure force and the gravitational force). Designations are the same as those for Fig. 1.

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