DELIVERY OF DUST PARTICLES AND SMALL BODIES TO PLANETS

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1. Introduction. Based on our studies presented in [1-7], below we discuss the probabilities of collisions of migrating small bodies and dust particles produced by these bodies with all planets and the delivery of water and volatiles to the planets. Our papers can be found on astro-ph and http://faculty.cua.edu/ipatov/list-publications.htm.

2. Calculation of the probabilities of collisions of migrating bodies and dust particles with planets. The probabilities were calculated based on the time variations of orbits of objects (bodies and particles) during their dynamical lifetimes (until all objects reached 2000 AU from the Sun or collided with the Sun). In our calculations [1-7], planets were considered as material points, so literal collisions did not occur. Using the algorithm [8] with the correction that takes into account a different velocity at different parts of the orbit [1], and based on all orbital elements sampled with a 10-500 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 of a collision of all N objects with a planet during dynamical lifetimes of objects. The probabilities of collisions of bodies and particles at different β (where β is the ratio between the radiation pressure force and the gravitational force) with all planets are presented in [7].

For calculation of the probabilities presented in [1-7], we did not take into account the destruction of bodies and particles during their migration and the sublimation (thermal evaporation) of dust particles. The role of collisions and sublimation is especially important for small particles. In our calculations, a small fraction of test Jupiter-family comets (JFCs) moved inside Jupiter's orbit for a long time (up to $\sim10^8$ yr). Actually JFCs turn into mini-comets and dust during such large times, but on average the values of P for the formed objects could be not smaller than for JFCs. For studies of the motion of mini-comets, the YORP effect must be taken into account. Di Sisto et al. [9] estimated that on average a JFC will experience a major splitting every 77 revolutions. In our opinion, large (e.g., >100 km) planetesimals entering inside Jupiter's orbit could be still large when they collided with planets.

Our calculations were made mainly for direct modelling of collisions with the Sun, but we obtained [5] that the mean probabilities of collisions of considered bodies with planets, the lifetimes of the bodies that spent millions of years in Earth-crossing orbits, and other obtained results were practically the same if we suppose that bodies disappear when perihelion distance becomes less than the radius of the Sun.

3. Probabilities of collisions of migrating small bodies and dust particles with planets. The probability P_E of a collision of a JFC with the Earth exceeded $4\cdot10^{-6}$ if initial orbits of considered bodies were close to those of several tens of JFCs, even excluding a few bodies for which the probability of a collision of one body with the Earth could be greater than the sum of probabilities for thousands of other bodies. The ratios of probabilities of collisions of JFCs with Venus, Mars, and Mercury to the mass of a planet usually were not smaller than those for Earth. For most considered bodies, the probabilities P_{Me} of their collisions with Mercury (exclusive for Comet 2P/Encke, for which $P_{Me}{\sim}P_E$) were smaller by an order of magnitude than those with Earth or Venus.

For dust particles produced by comets and asteroids, P_E was found to have a maximum (~0.001-0.02) at $0.002\le\beta\le0.01$, i.e., at diameter d~100 μm. (This value of d is in accordance with observational data). These maximum values of P_E were usually (exclusive for Comet 2P/Encke) greater at least by an order of magnitude than the values for parent comets. Probabilities of collisions of most considered particles with Venus did not differ much from those with Earth, and those with Mars were about an order of magnitude smaller. For particles produced by Halley-type comets, P was greater for Mercury than for Mars.

Probabilities of collisions of JFCs with Saturn typically were smaller by an order of magnitude than those with Jupiter, and the values of P for Uranus and Neptune typically were smaller by three orders of magnitude than those for Jupiter. 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.

For considered particles and bodies, the probabilities of their collisions with Jupiter $P_J<0.1$. The values of P_J can reach 0.01-0.1 for bodies and particles initially moved beyond Jupiter's orbit or in Encke-type orbits. For bodies and particles initially moved inside Jupiter's orbit, P_J is usually smaller than 0.01 and can be zero. The probabilities of collisions of migrating particles (exclusive for trans-Neptunian particles) with other giant planets were usually smaller than those with Jupiter. The total probability of collisions of any considered body or particle with all planets did not exceed 0.2.

4. Probabilities of collisions of migrating small bodies and dust particles with the Sun. Collisions of planetesimals with a star can cause variations in observed brightness and spectrum of the star. In our calculations, the fraction P_{Sun} of comets collided with the Sun during their dynamical lifetimes was about a few percent. For most JFCs, dynamical lifetimes are less than 10 Myr, and on average P_{Sun}~0.02. For dust particles, P_{Sun} depends on β and can be considerably greater than for their parent bodies. For example, for Comet 10P/Tempel 2, P_{Sun}~0.01, and almost all particles produced by this comet collide with the Sun [4].

4. Delivery of water and volatiles to the terrestrial planets. Using P_E=4·10^{-6} and assuming that the total mass of planetesimals that ever crossed Jupiter's orbit was about 100m_E [10-11], where m_E is the mass of Earth, we concluded [1-3,5] that the total mass of water delivered from the feeding zone of the giant planets to Earth could be about the total mass of water in Earth's oceans. (Similar conclusion was made in [12] based on other calculations.) We supposed that the fraction of water in planetesimals equaled 0.5. The ratio of the mass of water delivered to a planet by Jupiter-family and Halley-type comets to the mass of the planet can be greater for Mars, Venus, and Mercury, than that for Earth. This larger mass fraction would result in relatively large ancient oceans on Mars and Venus. The larger value of *P* for Earth we have calculated compared to those presented in [13-14] is caused by the fact that Levison et al. [14] did not take into account the gravitational influence of the terrestrial planets, and Morbidelli et al. [13] considered low-eccentric initial orbits beyond Jupiter's orbit. Besides, we considered a larger number of bodies. The detailed discussion on delivery of water and the comparison of our results with the results by other authors were presented in [5]. The delivery of volatiles to the terrestrial planets was discussed in [15].

In many recent papers (e.g., [13,16,17]), it is supposed that the outer asteroid belt was the main source of the delivery of water to the terrestrial planets. Drake & Campins [18] 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. To our previous discussion of the deuterium/hydrogen paradox of the Earth's oceans presented in [5], we can add that Genda & Ikoma showed [19] that D/H in the Earth's ocean increased by a factor of 2-9. Another explanation of the D/H paradox was given by Owen [20], who supports that most of the water was delivered to the Earth by comets. Horner et al. [21] suggested that comets which formed in different regions of the solar nebula should have measurably different D/H ratios and the ratio at 10 AU is about the same as that for Earth's water. Muralidharan et al. [22] studied direct adsorption of water onto the surfaces of dust grains prior to planetary accretion. They concluded that many Earth oceans of water could be adsorbed.

For the present Solar System, *the total amount of material delivered by dust to the Earth* can be less than the amount delivered by all bodies only by a factor of several. Ceplecha [23] obtained that the objects with masses m<10^{15} kg (the last mass corresponds to diameter d of 10 km) contribute by 10^{8} kg per year per Earth's surface and the influx for particles with m<10^{-7} kg is (2-6)·10^{6} kg/yr. In [24-25] the total dust influx to the Earth is estimated to be (2-4)·10^{7} kg/yr. Based on the probabilities of collisions of near-Earth objects (NEOs) with the Earth, we [12] obtained the influx of 10^{8} kg/yr for bodies with d<10 km and 6·10^{8} kg/yr at d<40 km (the diameter of the largest NEO).

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