MIGRATION PROCESSES AND VOLATILES INVENTORY TO THE INNER PLANETS.

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Introduction. Comets and asteroids colliding with the terrestrial planets can deliver volatiles and organic or prebiotic compounds to the planets, thereby depositing on the planets the fundamental building-blocks for life [1]. The inner planets contain heavier and cosmically less abundant elements in an iron-silicate matrix than the giant planets. This can be caused by the following three mechanisms: uneven fractionation and condensation in the accretionary disk; unequal degree of degassing of the composed matter; and heterogeneous accretion [2]. Asteroid-size bodies consisting of the last low-temperature condensates (similar to most primitive chondritic meteorites, and enriched in hydrated silicates and trapped gases) are believed to have fallen onto the inner planets during the process of the giant planets formation. The relative contribution of either endogenous (i.e. outgassing) or exogenous (i.e. asteroid/comet collisions) sources is difficult to assess, although it is constrained by the pattern of noble gas abundances in the planetary atmospheres [3].

A Model of Migration of Icy Objects to the Terrestrial Planets. Migration of planetesimals from the feeding zones of the giant planets and trans-Neptunian objects (TNOs) to the orbit of Jupiter was investigated by several authors. Therefore we studied the orbital evolution of Jupiter-crossing objects (JCOs). Evolution of 25000 virtual JCOs under the gravitational influence of all the planets, except for Pluto (and in some cases Mercury) were numerically modelled for intervals $T_S \geq 10$ Myr (see [4-5] for more details). After 10 Myr, testing was carried out to determine whether some of the remaining objects could still evolve into orbits inside Jupiter's orbit. If so, the calculations were continued.

We performed several series of runs. In the first series ($n1$), 3100 bodies having orbits close to those of 20 real Jupiter-family comets (JFCs) with periods $5<P_a<9$ yr were modeled, and in the second series of runs ($n2$) we considered 10000 JCOs moving in initial orbits close to those of 10 other JFCs with periods $5<P_a<15$ yr. In other series, initial orbits were chosen close to those of several known comets. The probabilities of collision of these objects with the inner planets, and times spent in different orbits (e.g., Aten and Apollo orbits), during the lifetime of an object were calculated based on their orbital elements calculated with time steps of 500 yr. From these calculations, we deduced the mean probabilities and respective collision times for all the objects.

To achieve this, we used the Bulirsh-Stoer method (BULSTO code) with the integration step error less than $\varepsilon \in [10^{-9}$-$10^{-8}]$ and in some runs $\varepsilon \leq 10^{-12}$, or a symplectic method (RMVS3 code) from the integration package of Levison and Duncan [6]. Both the symplectic method at an integration step $d_s \leq 10$ days and BULSTO code at the above mentioned ε values essentially gave similar values for the mean collision probabilities and characteristic times spent in different orbits with similar initial data. The two methods gave different values for the probability of collisions with the Sun in the case of frequent close encounters with the Sun but gave the close values for collisions with the planets even in this case.

The results for evolution of the objects showed considerable variation between different runs. A few ($\sim$0.1 %) bodies, mainly in the series with 2P and 10P orbits, achieved and retained typical Apollo orbits with a semi-major axis $a<2$ AU, or even Amor or inner-Earth object (IEO) orbits for 10^6 – 10^8 years. For the $n1$ series, the mean collision probability of a JCO with the Earth during lifetime of the JCO was found to be $P_E = 4.5 \times 10^{-6}$ for BULSTO. The mean value for all objects from the $n1$ series with RMVS3 code is $P_E = 40 \times 10^{-6}$, but $P_E = 4.8 \times 10^{-6}$ if we exclude only one object in the orbit of 46P comet playing the crucial role. For the $n2$ series $P_E \approx 15 \times 10^{-6}$ both for BULSTO and RMVS3. In one JCO series, P_E varied from 10^{-6} (39P with BULSTO) to more than 10^{-4} (2P with both BULSTO and RMVS3).

Collision probabilities with the inner planets were similar both for actual encounters with the Sun and if objects reaching perihelion distances q less than several radii r_S of the Sun were omitted. If orbits for the comets 2P and 10P with $q<2r_S$ were included, resulting in some collisions with the Sun, objects with inclination $i>90°$ were produced. Almost no such objects resulted if $q<2r_S$ orbits were omitted.

The specific mass of matter delivered by JCOs to an inner planet (normalized to its mass) turned out nearly the same for Earth and Venus though greater for Mars.

Volatiles Inventory to the Inner Planets. Assuming that the mean collision probability of JCOs with the Earth is $P_E = 4 \times 10^{-6}$ and the total mass of planetesimals M_{pl} that crossed Jupiter's orbit is $\sim 100 m_\oplus$ (where $m_\oplus$ is the mass of the Earth), we find that the total mass of bodies which impacted the Earth is $4 \times 10^{-4} m_\oplus$.

If ices represent half of this mass, then the total mass of ice that was delivered to the Earth from the feeding zone of the giant planets is roughly equal to the mass of the Earth's oceans. Mars accreted more comets per unit of a planet mass than Earth and Venus. This supports the idea of a relatively large ancient ocean on both Mars and Venus.

Our estimate of the water inventory to the early Earth is greater than those of Morbidelli et al. [7] and Levison et al. [8]. This discrepancy is probably because (a) they used a relatively small number of objects in their modelling, (b) they did not consider migration of bodies into the orbits with aphelion distance Q<4.2 AU and q<1 AU, and (c) Levison et al. [8] did not take into account the influence of the terrestrial planets. Morbidelli et al. (2000) obtained $P_E = (1-3) \times 10^{-6}$ in the 5-8 AU region, which is close to some of our estimates. Their value of M_{pl} is smaller, possibly because they neglected migration of planetesimals to Jupiter's orbit caused by their mutual gravitational perturbations.

Laboratory experiments on the trapping of gases in amorphous ice forming at low temperature [3] suggest that this is an important mechanism for delivering noble gases to planets. The relative abundance pattern of argon, krypton, and xenon in the atmospheres of inner planets may then be partially explained if the efficiency of gas trapping is strongly dependent on temperature.

Similarly, the D/H ratio of H_2O molecules in Comets Halley, Hyakutake, and Hale-Bopp is nearly twice that of seawater. This discrepancy may be caused by the deuterium enrichment near Jupiter being different from that in more distant colder regions in the period before the heavy bombardment of the inner planets took place [9].

Conclusions. One may assume that both endogenous and exogenous processes were responsible for the volatile gases in the terrestrial planets. Our simulations show that collisions of planets with small objects are an important source of these volatiles and that the total mass of volatiles delivered to the Earth from the feeding zone of the giant planets is similar to the mass of the Earth's oceans.

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