VOLATILES INVENTORY TO THE INNER PLANETS DUE TO SMALL BODIES MIGRATION. M. Ya. Marov, *M.V. Keldysh Institute, Russian Academy of Sciences, Miusskaya sq. 4, Moscow 125047, Russia (marov@spp.keldysh.ru)*, S. I. Ipatov, *M.V. Keldysh Institute, Moscow; NASA/GSFC, Greenbelt, 20771, USA (siipatov@hotmail.com)*.

Introduction. Comets and asteroids' chondrites are addressed as remnants of the outer planets formation. These small bodies are assumed to encapsulate the primordial matter from which the planets were built up. Comets provide the link of our solar system with the Galaxy through influx inward the solar system due to tidal perturbation of the Oort cloud and by probing pristine material of the presolar cloud delivered by the comets. Migration and collisions of small bodies with the planets is a key to assess their potential contribution to the volatiles delivery and organic/prebiotic compounds, thereby advancing the basic concepts for life origin [1].

Unlike the giant planets which preserved essentially non-modified, the inner planets were formed by heavier and cosmically less abundant elements entering into the composition of an iron-silicate phase. Three fundamental mechanisms are thought to be concurently at work: uneven fractionation/condensation in the accretionary disk; unequal degree of degassing of the composed matter; and heterogeneous accretion [2]. Uneven condensation should result in a lack of low temperture volatiles (nitrogen, water, sulfur, carbon) in the region of terrestrial planets formation under temperatures of up to 1500 K and pressures less than 0.1 mbar.

After formation of the bulk of planetary mass, cometary-like and asteroid-size bodies consisting of the last low-temperature condensates (similar to most primitive chondritic meteorites enriched in hydrated silicates and trapped gases) are assumed to fall onto the inner planets during the final accretionary phase. Although the relative contribution of either endogeneous or exogeneous sources in the atmosphere/hydrosphere formation is difficult to establish, the late veneer deposits due to bombardment is supported by heavy cratering of the inner planets.

Migration Model and Results of Modeling. Basically, the idea for collisions and volatiles inventory is rooted in orbital dynamics of the various families of small bodies, specifically those evolving to become inner planets crossers. They involve near-Earth objects (NEOs), short- and long-period comets, trans-Neptunian objects (TNOs), and planetesimals from the feeding zone of the giant planets. These planetesimals and TNOs apparently played a great role in the inner planets evolution because these bodies consisted mainly of water and other volatiles.

Based on the earlier developed model of $5 \cdot 10^9$ 1-km TNOs within 30<a<50 AU [3] it was assessed that now $\sim$10,000 and several hundreds of these bodies move in Jupiter-crossing and Earth-crossing orbits, respectively. The new developed model is focused on the quantative analysis of orbital evolution of Jupiter-crossing objects (JCOs) and probabilities of their collision with the inner planets.

Evolution of $\sim 10^4$ virtual JCOs under gravitational influence of all planets, except for Mercury and Pluto, was numerically modeled for intervals $T_S \geq 10$ Myr with an integration time step 500 yr. Below only the results obtained with the use of the method by Bulirsh and Stoer (BULSTO code) are presented, the relative error per integration step being less than ε which was taken between 10^{-9} and 10^{-8}. For $\varepsilon \leq 10^{-12}$ and for a symplectic method we obtained similar results, exclusive of probabilities of collisions with the Sun. Several series of runs were performed. In the first series of runs (n=1) bodies having orbits close to that of 20 real Jupiter-family comets with periods $P_a < 10$ yr were considered. In other series the initial orbits were selected being close to those of several comets (2P, 9P, 10P, 22P, 28P, or 39P).

The total impacting probability P_Σ and the total time interval T_Σ to reach perihelion distance q less than a semi-major axis of a planet were evaluated for all N objects, and then impact probabilities per one object $P_r = 10^6 P = 10^6 P_\Sigma / N$ and $T_r = T_\Sigma / N$ during T_S were estimated. Note that for calculations of such probabilities we used the orbital elements obtained with a step of 500 yr, but didn't integrate collisions with planets. The results for Venus (V), Earth (E), and Mars (M) are shown in Table 1. Data for two JCOs having the highest probabilities of collisions with the terrestrial planets (1.0 and 0.5, respectively) were not included in the Table. The last line for N=7349 doesn't also include series '2P'.

The mean probability of collisions with the Earth for the modeled 7850 virtual JCOs during their lifetimes turned out $P = 2 \cdot 10^{-5}$ (though it is $P = 8 \cdot 10^{-5}$ for 7852 objects including those two with highest collisional probabilities), but we consider mostly objects with a relatively large probability. So below we consider $P = 6 \cdot 10^{-6}$, which is a little more than for n=1. Larger (than those obtained by other scientists) mean probabilities of collisions with the terrestrial planets are caused mainly by that we considered a larger number of initial objects and among them there were objects with large collision probabilities. Specific mass of the matter delivered by JCOs to an inner planet (normalized to its

Table 1: Values of T (in Kyr) and P_r (Venus=V, Earth=E, Mars=M)

		V	V	E	E	M	M
	N	P_r	T	P_r	T	P_r	T
n=1	1900	2.4	4.23	4.51	7.94	6.1	30.0
$2P$	501	141	345	110	397	10.5	430
$9P$	800	1.3	1.76	3.72	4.11	0.7	9.73
$10P$	2149	28	41.3	35.6	71.0	10.3	169.
$22P$	1000	1.4	2.98	1.76	4.87	0.74	11.0
$28P$	750	1.7	21.8	1.9	34.7	0.4	69.
$39P$	750	1.1	1.72	1.2	3.0	0.3	6.82
$total$	7850	18	37.7	18.8	51.5	5.3	85.9
$total*$	7349	9.5	16.2	12.6	27.9	4.9	62.4

mass) proves to be nearly the same for Earth and Venus though greater for Mars. The total collisional probability with the inner planets is mainly caused by a small ($\sim$ 0.01-0.001) fraction of bodies residing in orbits deep inside Jupiter's orbit for more than 1 Myr. Of the objects under study seventeen bodies moved in Apollo orbits with a<2 AU during at least 0.5 Myr each one. A few objects got Aten orbits. More details on specifics of the runs performed can be found in the papers by Ipatov (see htpp://arXiv.org/archive/astro-ph, e.g., astro-ph/02-05250, astro-ph/0210131, astro-ph/0211618, astro-ph/-0212177).

Volatiles Inventory. Based on the estimated mean collisional probability P=$6\cdot10^{-6}$ and assuming that 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) we found that the total mass of bodies impacted the Earth is $6\cdot10^{-4}m_\oplus$. If ices composed only a half of this mass, then the total mass of ices that were delivered to the Earth from the feeding zone of the giant planets turns out to be greater by a factor of 1.5 than the mass of the Earth's oceans. During the following 4 Gyr the effectiveness of transport was much lower and less than 0.1% of the total mass of volatiles was delivered. Specific mass of the volatiles accumulated by a planet at the expense of former JCOs is greater for Mars than for Earth and Venus that results in the relatively large ancient oceans on all these planets.

A fractionation pattern of noble gas abundance measured in the atmospheres of Earth, Mars, and Venus is addressed as an important constraint on the relative importance of comets and asteroids' chondrites in the delivery of volatiles. Strong argument was found in the laboratory experiments on the trapping of gases in amorphous ice forming at low temperature [4,5]. The relative abundance pattern of argon, krypton, and xenon in the atmospheres of inner planets could be partially explained by such a mechanism of strongly temperature dependent gas trapping. Although the concurence between internal degasing and input of volatile-rich materials from outer regions of the solar system remains unclear, heterogeneous accretion is thought to be an important contributor to the observed ratios of different species in the current atmospheres of the planets.

Summary. The concurrent processes of endogeneous and exogeneous origin are assumed to be responsible for the volatile reserves in the terrestrial planets. Volatiles inventory through collisions is rooted in orbital dynamics of small bodies including NEOs, short- and long-period comets, and TNOs, the latter probably supplying a large amount of JCOs.

Our model testifies that even a relatively small portion (~ 0.001) of JCOs which transit to orbits with aphelia inside Jupiter's orbit (Q<4.7 AU) and reside such orbits during more than 1 Myr may contribute significantly in collisions with the terrestrial planets. The total mass of volatiles delivered to the Earth from the feeding zone of the giant planets could be greater than the mass of the Earth's oceans.

Acknowledgements. This work was supported by RFBR (02-02-16165 and 01-02-17540), NRC (0158730), NASA (NAG5-10776), and INTAS (00-240),

References: [1] Marov M. Ya. and Ipatov S. I. (2001) *Collisional processes in the solar system*, ed. M. Ya. Marov and H. Rickman (ASSL) 261, 223-247. [2] Marov M. Ya. and Grinspoon D. (1998) *The Planet Venus*, Yale University Press. [3] Marov M. Ya. and Ipatov S. I. (2002) *Migration Processes and Volatiles Delivery*, Paper presented at the IAU Symposium ”Bioastronomy 2002: Life Among the Stars”, Hamilton Iceland, Australia, July 2002. [4] Notesco G., Laufer D., Bar-Nun A., and Owen T. (1999) *Icarus* 142, 298-300. [5] Owen T. C. and Bar-Nun A. (2001) *Collisional processes in the solar system*, ed. M. Ya. Marov and H. Rickman, (ASSL) 261, 249-264.