IMPACT EROSION OF ATMOSPHERE: SOME RESULTS OF NUMERICAL SIMULATIONS FOR VERTICAL IMPACTS. V. V. Svetsov, Institute for Dynamics of Geospheres, Russian Academy of Sciences, Leninskiy Prospekt 38-1, Moscow, 119334, Russia, svetsov@idg.chph.ras.ru.

Introduction: Atmospheric cratering by impacts could result in substantial losses of atmospheres in the course of planetary evolution [1, 2]. However the values of atmospheric masses escaping planets after impacts and impactor masses retained by planets still remain to be determined with necessary accuracy. A simple tangent-plane approximation [3] and the model of angular-dependent vapor-atmosphere interaction [4] are imperfect and too crude [5, 6]. Numerical simulations [7, 8] of vertical impacts of comets and asteroids from 1 to 30 km in size at 20–50 km/s show that the losses of the modern Earth atmosphere after these impacts are less than the amounts of volatiles delivered by the impactors. Estimates [6] show that the impacts of bodies smaller in diameter than 1 km are likely to be more efficient in atmospheric erosion because (as a first approximation) the escaping mass of heated air is proportional to an impactor cross-section while the supply with atmophile elements is proportional to an impactor mass. In this study numerical simulations of vertical impacts have been made for impactor diameters D from 75 m to 10 km and velocities V from 15 to 70 km/s. The aim was to calculate the losses of air and retained masses of impactors.

Numerical Procedure: The computational technique was similar to that used in [7, 8]. The hydrodynamic method SOVA [9] was applied to the simulations that included the stages of a flight through the atmosphere, an impact at a target, and a flow of air, target and projectile materials to altitudes above 100–200 km. A nonuniform grid had 20 cells across the impactor radius. The simulations were carried out for the modern atmosphere of the Earth. The equation of state [10] was used for air. The impactor shape was taken as a cylinder with its diameter equal to its height. The Tillotson EOS [11] of granite was used in the simulations for asteroids. The cometary impactors were treated as icy bodies, a tabulated EOS for water obtained by Smetannikov [12] was used for them. It was assumed that a target is made of the same material with the same EOS as the impactor.

Numerical Results: Masses of air that acquire velocities higher than 11.2 km/s and escape the Earth gravity after impacts are shown in Fig. 1 as functions of projectile diameters and velocities. A wake left by impactors in the atmosphere plays an important role in acceleration of heated air. The simulations show that if $D<He^{1/2}/V$ (where H is the scale height and e is the specific internal energy of air) the wake is substantially thinner than H, the air cannot acquire high speed, and only an insignificant air mass escapes the planet. The relative air losses dramatically increase with increasing D to 100–300 m and then gradually diminish. For D greater than 10–30 km, when the atmosphere is too thin to influence the flow of a vapor plume, the ratio of escaping air mass to impactor mass is bound to be proportional to $1/D$.

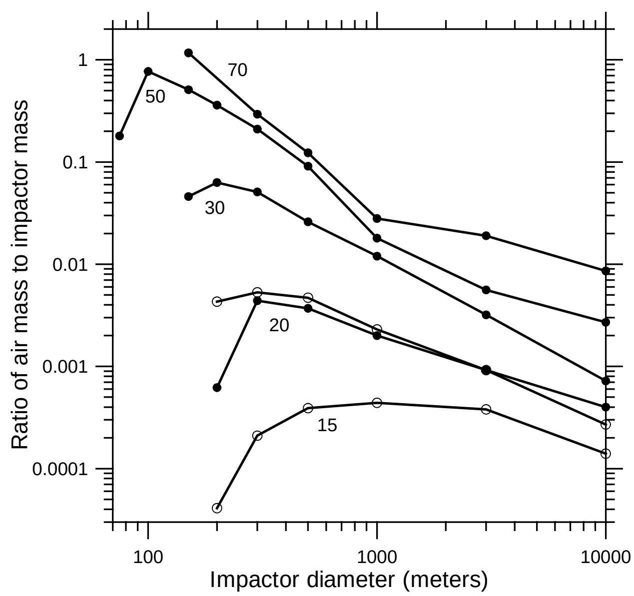

Fig. 1. Atmospheric masses (normalized to impactor masses) lost after impacts. Impactor velocities are indicated at the curves in km/s. Results for asteroids are shown by open circles and for comets by solid circles.

Any asteroid striking the Earth at a typical velocity 15 km/s expels an air mass no more than 0.05% of the impactor mass. Almost all the impactor is vaporized and retained by the Earth. In assumption that the asteroidal impactors are 20% carbonaceous chondritic, average carbon dioxide contents in asteroids is about 0.01 [13], much higher than the air losses. Therefore, a 1 bar atmosphere on the Earth grows under asteroidal impacts mainly due to CO_2 supply. In this case the atmospheric growth rate depends on a mass accretion rate and only slightly on an impactor mass spectrum. To a first approximation, at a given V, the ratio of an escaping atmospheric gas to an impactor mass for relatively small impactors is proportional to $\rho_0 H/\rho_m D$, where ρ_0 is the atmospheric density at the planet surface and ρ_m is the impactor density [6]. Consequently, the growth of an atmosphere on the Earth will continue as long as a mass accretion rate is sufficiently high.

Only a small fraction of impactor material can escape the Earth if $V \leq 30$ km/s and, hence, volatile-rich short-period comets (their mean velocity is about 20 km/s) also supply the atmosphere with atmophiles. Even a 1-km-diameter long-period comet striking the Earth at 50 km/s would enlarge the atmosphere mass because no more than half its mass (for $D \leq 10$ km) escapes the Earth (with a 1 bar atmosphere), whereas a potential cometary CO_2 content is likely to be no less than 20%. (About 15% of an icy comet impacting vertically would be retained by the Earth if the atmosphere were absent). However oblique impacts of long-period comets may be more efficient in atmospheric expulsion and less in atmophile supply so that some atmospheric erosion could occur during a late cometary veneer. On the other hand, it is hardly probable that the atmospheric losses after oblique impacts of asteroids prove to be so high that this violates the conclusion about the permanent growth of the Earth atmosphere (without sinks other than impact erosion).

Results Applicable to Mars: Air masses that acquire velocities above 5 km/s have been also calculated (Fig. 2). These masses would escape Mars attraction if a similar 1 bar atmosphere existed on Mars. About 70% of incoming asteroids strike Mars at velocities below 10 km/s [13]. These bodies do not vaporize [14] and can supply the atmosphere with volatiles mainly through subsequent outgassing. However they expel some amount of atmospheric gas. Faster asteroids vaporize and after impacts supply the atmosphere with CO_2 and other atmophiles if they are large. This atmophile deposition dominates over the erosion produced by the impactors with velocities below 10 km/s. Smaller fast impactors (D<1 km for V= 15 km/s) expel the atmospheric gas. For typical mass spectra and a large enough range of impactor sizes a 1 bar atmosphere on Mars would grow under vertical impacts of asteroids. The numerical results show that the same is true for short-period comets.

If the atmosphere grows, larger asteroids expel the atmosphere. The atmosphere growth will be restricted by the largest impactors in the mass distribution. In contrast to the Earth, given mass spectrum exponent, the largest impactor, and impactor compositions, a steady-state solution with a certain atmospheric mass on Mars is bound to exist for the equation of atmospheric mass variation (impact erosion against atmophile supply by impactors, with other sinks and outgassing neglected). In this model smaller impactors expel the atmosphere while larger ones supply it with atmophiles, contrary to the tangent plane model applied to Mars in [13]. However further numerical simulations including oblique impacts are necessary for reliable quantitative conclusions and construction of an adequate model of atmospheric evolution on the terrestrial planets.

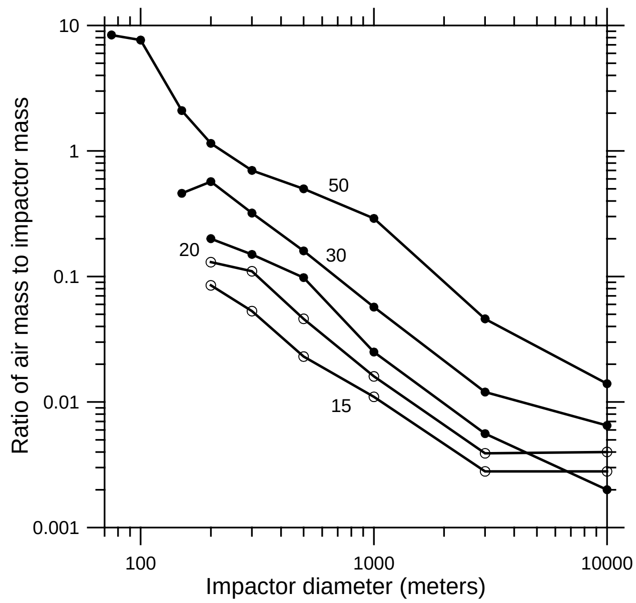

Fig 2. Atmospheric masses that acquire velocities above 5 km/s. Symbols are the same as in Fig. 2.

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