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Impact erosion of cosmic objects

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Abstract

The masses of target and projectile material which escapes from a target after the impacts of small stony projectiles have been calculated in the approximation of a flat atmosphereless target. The results are applied to the growth of planetary embryos at a high-velocity (~1−10 km/s) stage of accretion. Impact erosion during Mercury formation is considered as an alternative to the popular hypothesis of a huge impact which stripped away Mercury's original mantle.

1. Introduction

Collisions of cosmic objects played a major role during the early evolution of the planets. The impacts could result in disruption or mass losses of colliding planetesimals and planetary embryos. The models of planetary accretion (e. g., [2]) usually take into account only a catastrophic collisional disruption when the impact kinetic energy per unit target mass exceeds some threshold value [1]. However, the impacts of small bodies with energies well below this threshold can cause significant collisional erosion when the velocity of ejecta from a crater exceeds the escape velocity of a target. Experiments provide estimates of the amount of lost target material [3] but retained masses of impactors are poorly known.

2. Calculations of mass losses

I have carried out 3D numerical simulations of impacts with velocities from 1.25 km/s to 60 km/s on a flat target, using a hydrodynamic method SOVA [5]. Both the projectile and the target were assumed to consist of dunite with a density 3.3 g/cm^3. The losses of target and projectile masses were calculated for impact angles from 0 to 90 degrees and then were averaged over the angles. If the sizes of impactors are much smaller than target sizes the impact outcome is independent on these sizes. The results are shown in Figs. 1, 2. For each cosmic object with a certain escape velocity there is some impact velocity at which the escaping target mass is exactly compensated by the retained mass of impactors. The Moon, Mercury and asteroids of the main belt lose their masses under asteroid impacts with the current mean velocities (18, 35 and 5 km/s).

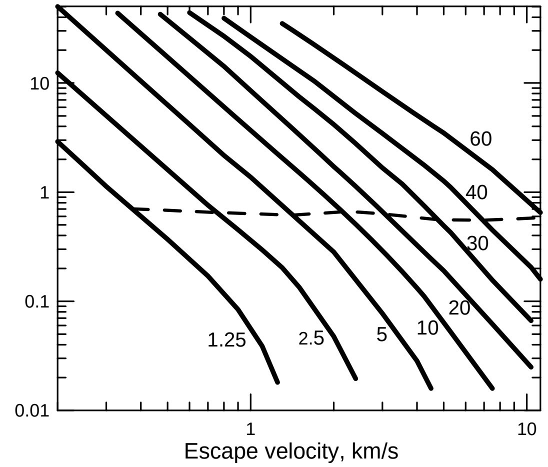

Figure 1: Target mass ejected with a speed above escape velocity is plotted versus escape velocities. Impact speeds are shown in km/s at the curves. Points where target losses are equal to retained impactor masses are connected by the dashed line.

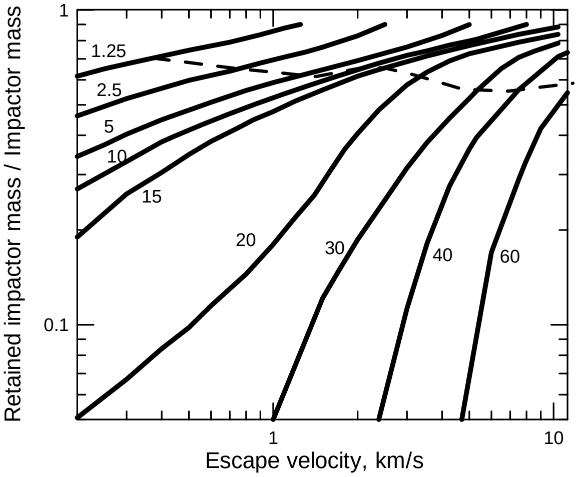

Figure 2: Retained mass of impactors as a function of escape velocity for various impact velocities.

3. Erosion of planetary embryos

I have calculated a relative growth rate of stony planetary embryos with various sizes under bombardment of small stony planetesimals, using the losses and increase in mass described above. It was assumed that the flux of planetesimals is the same in the vicinity of all embryos. The result substantially depends on mean collisional velocities V_∞. For V_∞=1.25 km/s stony embryos grow in size if their diameters *D* are larger than 600 km. For V_∞=5 km/s the bodies grow if D>2000 km, and smaller embryos vanish. If the planetary embryos are differentiated they shed their silicate shells. Metallic cores of smaller embryos grow if differentiation goes during the planetesimal bombardment and imactors are rich in metals as, e.g., ordinary H-chondrites.

Calculations on the subject of Mercury formation show that if a differentiated proto-Mercury had chondritic average abundance (core mass equal to 1/3 of the total mass *M*) it could come to its final current state (with the core mass about 2/3 *M*) under the flux of enstatite or ordinary chondrites if projectile velocities V_∞ were ~15 km/s and higher. If V_∞ were equal to 30 km/s, the proto-Mercury had to be more massive by 40%. At V_∞=15 km/s the proto-Mercury, about 0.2 of the modern mass, grows to the final mass through a state with a very thin silicate shell.

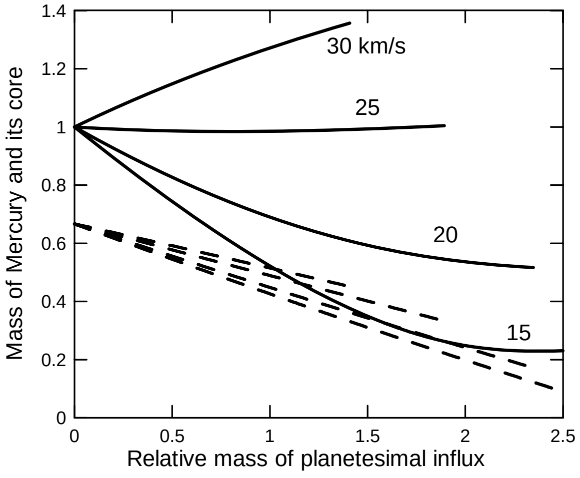

Figure 3: Mercury mass (solid curves) as a function of a mass to be accreted before achievement of the final (current) state of Mercury. Impact velocities are from 15 to 30 km/s. Dashed curves: evolution trajectories of metallic cores. Time goes to the left.

4. Discussion and Conclusions

The impact velocity is the main factor determining the growth of planetary embryos. At the early stages of embryo growth the planetesimal impact velocities are small but they can reach 5 km/s in some million years after the beginning of evolution of planetesimal assemblage [4]. Then stony embryos which are smaller than 2000 km in diameter erode and become metallic. Small debris of the impacts can be removed from the inner solar system by solar wind and radiation in gas-free conditions. (The early dissipation of the nebular gas is very likely [6].) The collisions with planetesimals deliver to the embryos roughly the same mass as embryo-embryo collisions at lower velocities [2], [4]. First, the collisional erosion can lead to a deficit of planetary embryos in comparison with scenarios of planetary accretion developed recently. Second, the peculiar properties of Mercury can be explained by formation of a large number of small iron embryos at 0.3−0.5 AU where impact velocities are higher and by erosion of a proto-Mercury mantle by planetesimal impacts with speeds ~10 km/s at a later stage of accretion.

Acknowledgements

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