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The Late Heavy Bombardment and deficiency of impact vapour condensate on the Moon

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Abstract

The origin of impactors which have caused the Late Heavy Bombardment (LHB) is not quite clear. In various researches, the preference was given both to stony bodies and to comets. The deficiency of lunar vapour condensate found recently can impose some constraints on the nature of impactors. Estimates of condensate masses, based on numerical simulations of the impacts on the Moon, show that the deficiency of condensate agrees with recent suppositions that comets prevailed in the flux of LHB projectiles.

1. Introduction

In many papers, LHB has been interpreted as an impact spike primarily caused by asteroids (e.g., [1]). However, some recent researches support the importance of comets. The Earth's early record of iridium and the corresponding lunar record suggest that the bulk of the LHB flux was cometary [2]. Dynamical models show that migration of giant planets could produce an influx of bodies in which the total mass delivered to the Earth-Moon system by asteroids was an order of magnitude smaller than the cometary contribution [3]. There is one feature of composition of lunar samples, which can impose constraints on properties of the bodies involved in LHB. It is obvious deficiency of condensed vapour [4], though amount of evaporated material at large impacts with high speeds, as generally agreed, should be considerable. I try to explain this discrepancy.

2. The problem of lunar vapour

The ultimate phase state of target material depends on shock wave pressure. The maximum pressures calculated from the Hugoniot relations are shown in Fig. 1. It follows that evaporation is insignificant if the velocities of stony impactors are below ~12 km/s or cometary impacts have speeds less than ~20 km/s. As major scenarios of LHB (except the accretion tail) predict higher velocities as well, the target should be vaporized. Impact melt breccia is commonly occurring component of the upper lunar crust but most lunar regolith samples contain only tiny quantity of condensed vapour. Condensate appears to be less than 0.001 times as abundant as impact melt breccia even though it seems easy to identify it due to its distinctive composition [5]. Till now it has been found with confidence only in one sample of Apollo 14 regolith breccia [4]. As condensed particles in the sample are accompanied by complementary material of impact evaporation-residue origin, they originated from two-phase material.

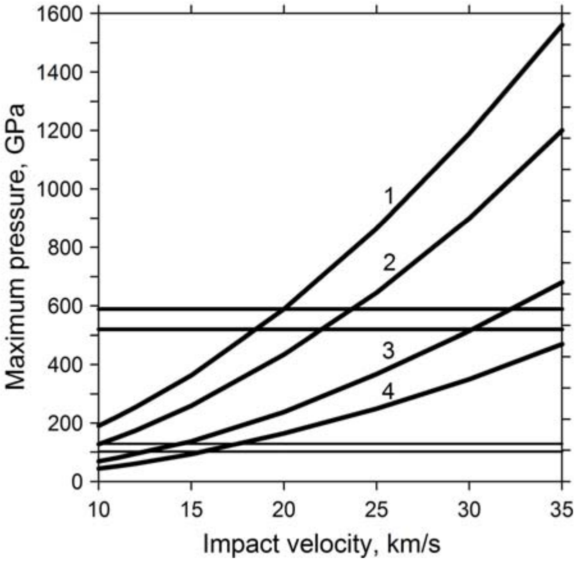

Figure 1: Maximum pressure behind a shock wave generated by the impact at a certain velocity for different materials of a target and impactor: 1 – dunite-dunite, 2 – granite-granite, 3 – impact of an icy body with density 1 g/cm^3 on granite target, 4 – icy impactor with density 0.6 g/cm^3 on granite target. The horizontal thin lines represent pressures of incipient vaporization of granite (130 GPa) and gabbroic anorthosite (100 GPa), thick horizontal lines are pressures of complete vaporization of the same materials (520 and 590 GPa respectively).

3. Results of numerical simulations

The target material compressed to the pressure of vaporization partially remains in a crater, forming a layer on its internal surface, and is partially ejected out from a crater and moves along ballistic trajectories. Two-phase material which remains in a crater can hardly generate condensed particles similar to those observed in the lunar sample. Ejecta lands at some distance from a crater (except for that part which escapes the Moon gravitation). The liquid phase of ejecta will fall on the Moon surface, and the vapour will be decelerated at a surface and remain over it until its condensation. This is the very probable mechanism of the separation of phases. The vapour concentration should not be small, that is, originally the material should undergo a pressure higher than that is necessary to start vaporization at unloading. This pressure is not known, and the properties of a target are insufficiently known also. As the first approximation, I assumed that the average initial pressure of two-phase ejecta is equal to half-sum of an incipient vaporization pressure and a complete vaporization pressure. For granite, this pressure is 325 GPa.

In order to calculate the mass which undergoes the pressures above this value and settles beyond the crater I have carried out 3D numerical simulations of impacts with velocities from 15 km/s to 35 km/s on a planar target, using a hydrodynamic method SOVA [6]. It was assumed that a granite 10-km-diameter projectile strikes a granite target at 45° to the surface. The results of simulations for various impact velocities are shown in Table 1. Using the modern velocity distribution of impacts on the Moon (with an average impact speed of 17.5 km/s), it is possible to find average masses of settled two-phase material, the total mass of melt and their ratio (M_e/M_m). This ratio has appeared to be somewhat less than 0.01.

Table 1: Relative masses of target melt (M_m), vapour remained in the crater (M_v), and vapor ejected and precipitated on the lunar surface (M_e). These masses are measured relative to the impactor mass.

V, km/s	M_m	M_v	M_e
15	3.9	0	0
20	9.0	0.04	0.015
25	13	1.0	0.22
30	15.5	2.5	0.39
35	17.5	3.8	0.55

4. Discussion and Conclusions

The estimate of the relative mass of condensate which can precipitate beyond a crater by an order of magnitude exceeds the estimate of condensate mass (<0.001) following from geochemical researches [4], [5]. Most of the breccias returned by the Apollo missions were formed in the lunar highlands about 3.9 – 4 Gyr ago, probably during LHB. Therefore, assuming that stony bodies made up only about 10% of impactors and that comets produced insignificant quantities of vapour but approximately the same amount of melt, we can explain the deficiency and 0.001 abundance of impact condensate. Nevertheless, the estimate cannot be the proof of a small share of stony bodies in the flux of LHB because of the model shortcomings. The data on the properties of lunar crust materials and vaporization shock pressures need refinement. Besides, it is necessary to estimate lunar gardening, losses of Moon mass due to impact escape and condensation efficiency.

Acknowledgements

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