IMPACT EJECTA ESCAPING THE MOON. V. V. Shuvalov (shuvalov@idg.chph.ras.ru) and N. A. Artemieva (artemeva@psi.edu), Institute for Dynamics of Geospheres, Leninsky pr., 38, bldg.1, 119334, Moscow, Russia.

Introduction: We calculate the mass of escaping ejecta on the Moon as a function of projectile type and impact angle. There are a few consequences associated with escaping material. The first one is connected with the Moon evolution after accretion – does it gain or lose the mass [1]? The second deals with weakly compressed escaping ejecta as a possible source of lunar meteorites [2]. Finally, we speculate on the chemical reactions within the escaping plume, which may change the lunar regolith composition [3].

Numerical model: High velocity impact on the Moon has been modeled using the 3D SOVA code [4] complemented by ANEOS [5] tabular equations of state for granite [6] and ice [7]. A total amount of escaping material M_{esc} (with ejection velocity exceeding 2.4 km/s) has been defined using tracer particle technique. The following types of projectiles have been modelled: stony asteroids with impact velocity of 18 km/s [8]; Jupiter family icy comets with velocity of 25 km/s [9]; and near-parabolic comets with velocity of 55 km/s [8]. In all cases impact angle varies from 15° to 90° (vertical impact). As high-velocity ejecta leave a crater at the early stage of crater growth, we can neglect strength and gravity. In this case hydrodynamic equations are self-similar, i.e. ejecta velocity distribution does not depend on the projectile size. Thus, all volume values may be measured in projectile volume V_{pr} (or mass), and later could be recalculated for an arbitrary impact event.

Results: The ratio of escaping (both, target and projectile) mass to initial projectile mass is shown in Fig.1. Asteroid impacts have a maximum of 4.2 at an impact angle of 45°, while in a vertical impact a small fraction (0.8) of the target material escapes with the projectile material characterized by velocity well below escape. Cometary impacts with substantially higher impact velocity of 25 km/s produce approximately the same amount of escaping ejecta with a maximum at 60° and a weak dependence on impact angle in the range of 45°-90°. In a shallow impact (<30°) only the projectile is escaping. Parabolic comets (impact velocity of 55 km/s) are able to eject much more target material – up to 10-12 of the projectile mass, and the cometary material itself usually escapes totally.

In principle, the results are sensitive to energy conservation options. The transfer of total energy deficiency (typical for the Eulerain numerical codes) into internal energy increases the volume of escaping ejecta. However, the effect is really strong ($0.83V_{pr}$ versus $0.34\ V_{pr}$) only in the case of a very low amount of escaping ejecta after a vertical impact, while for all other cases the difference is less than 10%. All results shown in the Figures have been obtained with the "energy conservation" option.

Our results differ substantially from O'Keefe and Ahrens (1977) estimates [1], which give the ratio of escaping material to gained material of 0.5 at 15-km/s impacts and of about 1 at 20 km/s impacts. This discrepancy can be easily explained by two factors: early calculations (a) had much lower resolution and (b) these calculations did not take impact obliquity into account. The results for a vertical impact are similar – the Moon gains its mass in impacts. However, our calculations across a wide range of impact angles give an opposite conclusion – the Moon loses its mass if the impact angle is in the range of 30°-60° (a half of all impacts are exactly within this range).

As a rule, high-velocity ejecta are highly compressed during the impact and escape as a mixture of melt and vapor. However, a fraction of this material from the uppermost layers of the target may escape in a solid state, creating lunar meteorites. Pressure-velocity distribution of ejecta after a 45-degree cometary impact is shown Fig.2.

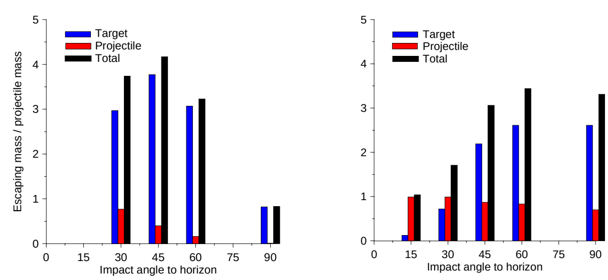

Fig.1 The ratio of escaping mass to projectile mass as a function of an impact angle. Asteroid impacts are on the left, cometary – on the right.

Moon mass through time: To interpolate the results of an individual impact to a long time interval, we should consider impact flux on the Moon and asteroid/comet ratio in this flux. While the former problem has been studied in detail with minor inaccuracy [10], the latter is still under discussion. Cometary input into total flux ranges between several percent [11,12] and 50-100% for large, 20-100 km diameter craters [13]. Recent astronomical observations show that the total amount of comets on cometary-like orbits is not larger than 18% [14]. For preliminary estimates, taking into account the fact that the comet-asteroid difference is not striking (Fig.1), we can totally neglect this difference. Thus, the value of escaping target material averaged over impact angles equals ~2. I.e. each impact event with projectile mass M_{pr} leads to target mass loss of $2M_{pr}$. Integrating a modern production function [10] from the smallest impact events to the largest one, we obtain a projectile mass flux of $3 \cdot 10^{15}$ kg/Gyr. Thus, the Moon loses about $6 \cdot 10^{15}$ kg/Gyr, or 10^{-7} of its mass. Overall losses during the last 3.9 Gyr (the age of the oldest maria on the Moon) could be 3 orders of magnitude higher because of more intensive flux at the end of the Late Heavy Bombardment.

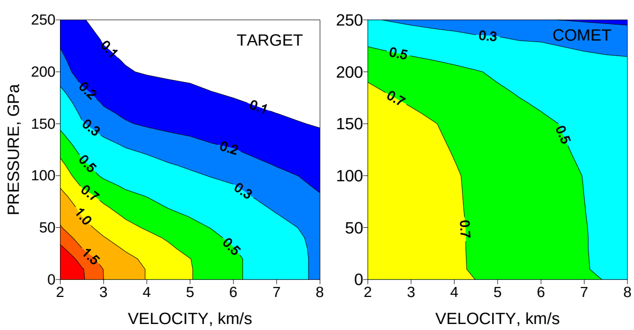

Fig.2 Cumulative amount of escaping material compressed in a shock wave above the pressure value shown on Y-axis and having velocity above the value shown on X-axis.

Lunar meteorites: Crater counts for the Moon [10] combined with CRE-age of the lunar meteorites (half of them spent <0.1 Myr in space [2]) support the "small impact" scenario with maximum parent crater of about 0.6-1 km. It means that the projectile size D_{pr} is not larger than 10-30 m, depending on impact conditions. This value is comparable with the thickness of the regolith layer [15]. Similar to martian meteorites [16], lunar meteorites (escaping ejecta with maximum compression of <32GPa – melting pressure for porous rocks [17]) come from a very thin layer near the surface (<$0.15D_{pr}$ for asteroids, and <$0.05D_{pr}$ for comets). Thus, the maximum burial depth should be less than 1 - 4 meters – this result is in an agreement with meteorites' 2π-exposure depth [2] and the fact that all meteorites are actually samples of the lunar regolith (http:/epsc.wustl.edu/admin/resources/meteorites/moon_meteorites_list.html). The total amount of solid escaping ejecta on the Moon is comparable with projectile volume, i.e. ejection efficiency of lunar meteorites is much higher than on Mars.

Our results on escaping ejecta with low shock compression should be considered as preliminary ones, as we neglect the highly porous regolith layer and treat the target as homogeneous intact rocks. As spall velocity is suppressed in damaged material [18], we may overestimate the total mass of solid escaping ejecta from small craters (in which excavation zone is totally within the regolith) by a factor of 2.

Roughly one-quarter to one-half of the ejected lunar material is reaccreted by the Earth within 10 Myr, with the largest fraction arriving within the first 50 kyr [19]. An interesting consequence may be connected with 83-km-diameter crater Tycho. ~100 Myr ago, the crater was created by 6-7 km-diameter projectile in an oblique (30-45°) impact. This impact event delivered 25-100 km^3 of lunar material to the Earth, i.e. our planet was uniformly covered by "Tycho" meteorites with average density 0.1-0.3 kg/m^2 (assuming 30% losses in the atmosphere). These massive deposits may be found in proper stratigraphic layers similar to the Ordovician meteorites [20].

Chemical reactions within the plume: Assuming pure granite (or basalt) as target material, compression above 150-200 GPa is needed for incipient vaporization. Our calculations show (see Fig.2) that at least 30% of escaping ejecta have been compressed above this pressure level. It means that the vapor phase mass is at least several percent of the projectile mass. Any volatiles in the target/projectile may increase this value substantially. Possible chemical reactions may lead to a thermal reduction of metallic oxides including iron, and losses of siderophile elements.

Acknowledgements: This study has been supported by RFBR grants 04-05-64338 and 05-05-64219.

References: [1] O'Keefe J.D. and Ahrens T.J. (1977) *Science 198*, 1249-1251. [2] Warren P. (1994) Icaurs 111, 338-363. [3] Yakovlev O.I. et al. (2006) this volume. [4] Shuvalov, V.V. (1999). *Shock Waves 9*, 381–390. [5] Thompson S.L. and Lauson H.S. (1972) SC-RR-61 0714. Sandia Nat. Laboratory, Albuquerque, NM.119 p. [6] Pierazzo et al. (1997) *Icarus 127*, 408-423. [7] Turtle E. and Pierazzo E. (2001) *Science 294*, 1326-1328. [8] Steel, D. (1998). *Planet. Space Sci. 46*, 473–478. [9] Shoemaker E.M.et al. (1994). In *Hazards due to Comets and Asteroids*, ed. by T.Gehrels, University of Arizona Press, 313-335. [10] Neukum G. et al. (2001) *Space Science Reviews* 96, 55-86. [11] Bailey M.E. and Stagg C.R. (1988) *Monthly Notices of the Royal Astronomical Society* 235: 1-35. [12] Levison H.F. et al. (2002) *Science* 296: 2212-2215. [13] Shoemaker E.M. (1998) In *Meteorites: Flux with Time and Impact Effects*, ed. by Grady M.M., Hutchison R., McCall G.J.H. and Rothery D.A. *Geological Society, London, Special Publications 140*: 7-10. [14] Binzel P.B. et al. (2004) *Icarus* 170, 259-294. [15] Oberbeck et al. (1973) *Icarus* 19, 87-107. [16] Artemieva N.A. and Ivanov B.A. (2004) *Icarus* 171, 84-101. [17] Stoeffler D. (1984) *J. Non-Cryst. Solids* 67, 465–502. [18] Head J. et al. (2002) Science 298, 1752-1756.. [19] Gladman B.J. et al. (1995) *Icarus 118*, 302-321. [20] Schmitz B. et al. (2001) *E&PSL 194*, 1-15.