DIRECT DELIVERY OF LUNAR IMPACT EJECTA TO THE EARTH.

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Large impacts into eastern hemisphere of the Moon cause hours to days long impact showers on the Earth with a chance for traces in terrestrial geological record.

Introduction: It is currently well understood that a portion of extraterrestrial material arriving to the Earth from space originates as lunar impact ejecta; known lunar meteorites are a small fraction of this material. Dynamics of delivery of lunar impact ejecta to the Earth has been numerically studied in detail by B. Gladman et al. [1]. An object launched by impact on the Moon with a velocity V exceeding the local lunar escape velocity V_{esc} can go directly to an Earth-crossing heliocentric orbit with a chance to encounter the Earth later, or to a Moon-crossing geocentric orbit with a chance to be perturbed by close encounter with the Moon and hit the Earth, or can head to the Earth directly, depending on launch position and direction. D. Gault and P. Schultz [2] have noted that after the largest lunar impacts, a significant mass of material is delivered to the Earth rather quickly, within decades, through the geocentric orbits, and thus may leave a prominent although yet undiscovered trace in the terrestrial geological record. Later, J. Fritz [3,4] has attributed some ^{3}He anomalies in Cenozoic sediments to delivery of lunar regolith from several particular recent large lunar impacts.

The total long-term-average proportion of material delivered from the Moon to the Earth on direct trajectories is small [1], for the present Earth-Moon distance; however for individual large impacts, direct delivery may be important. For example, the absence of exceptional meteor showers caused by direct delivery of ejecta has been used [5] as an argument against the alleged historical age of impact formed crater Giordano Bruno.

Here we analyze conditions of direct delivery of lunar ejecta to the Earth and possible effects related to such ejecta.

Direct Moon – Earth flights: The amount and arrival rate of directly delivered material from a given impact critically depends on position of the impact on the Moon. We perform an extended set of direct orbit integrations to overview the direct delivery regime. At each of 1212 points forming a uniform grid on the lunar sphere, we launch 2952 projectiles at 45º to the horizon in all azimuths with 5º intervals with different velocities ranged from V_{esc} = 2.4 km/s to 3.2 km/s. For even higher V the proportion of direct trajectories is very small, and we ignore them. We perform full orbit integration for a system that consists of the projectile, Earth, Moon, and Sun for 10 days or until the projectile hits the Earth. There are some "direct" trajectories through a very distal apogee that take longer than 10 days; however, their contribution is negligible and we ignore them. For the short dynamical integrations required, the choice of numerical technique is not important; we used MERCURY [6] with an algorithm that accurately treats close encounters, treating the Earth and Moon as uniform spheres.

To recalculate our test projectile counts into delivered ejecta mass, we assumed that the ejecta are uniformly distributed in azimuth, and that the cumulative mass ejected with velocity greater than V is proportional to $V^{-1.66}$ [7, 8]. With these assumptions, we calculated the V-dependent "weight" of each test projectile, as its percentage of the total mass escaping the Moon from a given crater. Thus, the list of projectiles delivered to Earth for a given crater gives usthe total directly delivered mass as a percentage of the total escaped ejecta. Knowing the arrival times of the projectiles to the Earth, we calculate the evolution of the mass delivery rate in percents per day.

Three examples of delivery rate evolution are shown in **Fig. 1**. Typically, ejecta arrive during a few hours (Giordano Bruno in Fig. 1) to days (Thales in Fig. 1). The map in **Fig. 2** shows all launch locations with the total amount of directly delivered material coded as an area of a circle, and the maximum delivery rate color-coded. The greatest total amount of directly delivered ejecta is ~2.2%; the highest rate is above 2 %/day, but it is hard to measure accurately because of discreteness of test projectiles.

Possible effects: To estimate an order of magnitude of the effects caused by a shower of directly delivered lunar ejecta, we consider a maximum case, crater Tycho. The "standard" impact scaling relationships [9] give the Tycho-foming rocky asteroid mass of 6×10^{14} kg, assuming the typical impact conditions (18 km s^{-1} at 45º). Dedicated modeling [8] has shown that for typical large asteroid impacts on the Moon, the mass ejected with $V > V_{\mathrm{esc}}$ is 1 – 4 masses of the crater-forming projectile, depending on conditions; we assume 2. Our calculated direct delivery efficiency is 1%. This gives 1×10^{13} kg delivered to the Earth on direct trajectories, or ~10 microns equivalent global layer of dust. The total delivered energy is 7×10^{20} J. This energy is equivalent to ~15,000 Tunguska events, or a single impact event producing ~20-km crater, or melting of 0.5 cm of global layer of temperate ice, or increase of the temperature of the whole atmosphere by 0.2 K. The peak delivered power is 1×10^{14} W. If spread evenly over the whole Earth, this gives energy flux of 0.2 W/m^2, negligible in comparison to both the solar radiation and typical weather-related energy fluxes in the atmosphere.

Possible effects of the ejecta showers crucially depends on the sizes of ejecta particles, and how evenly they are distributed. From lunar observations (distal rays and secondary clusters) we know that the sub-V_{esc} ejecta of large craters are very unevenly distributed, not uniformly as assumed here, and have a wide range of particle (or aggregate) sizes. It is natural to expect the same for super-V_{esc} ejecta, which makes assessment difficult. It is clear that the ejecta directly delivered during a few days to the rotating Earth are spread over the whole planet, but it is still unknown, how evenly. If the dominant mass of ejecta is fine dust and spread very evenly, the shower is just a spectacular show; in the opposite case it is very hazardous, but locally.

Chances for a terrestrial geological record: As we see, the showers of directly delivered lunar ejecta are not too catastrophic, and the chances to spot their traces in the geological record of the Earth are quite poor. Obviously, the best chances are the largest and \ most recent events. Of the three largest ($D > 70$ km) Phanerozoic-age craters on the Moon, only the youngest, Tycho (~105 Ma, $D = 82$ km) is inside the direct delivery zone and is the best candidate. Of smaller and younger craters, two have chances much higher than all others. One is Giordano Bruno (3 – 8 Ma, $D = 21$ km), the youngest crater of its size on the Moon. The other is Thales ($D = 32$ km). Its age is not constrained with samples, and we are not aware of any superposed crater counting results for this crater. However, according to its morphology and roughness, it is older than Giordano Bruno but certainly Cenozoic. It also has about the highest possible direct delivery efficiency (2%). Identification of the Thales event in the terrestrial geological record would be exceptionally valuable for lunar chronology.

References: [1] Gladman B. G. et al. (1995) *Icarus*, *118*, 302-321. [2] Gault D.E. & Schultz P.H. (1991) *Meteoritics*, *26*, 336-337. [3] Fritz J. et al. (2007) *Icarus*, *189*, 591-594. [4] Fritz J. (2012) *Icarus*, *121*, 1183-1186. [5] Withers P. (2001) *MPS*, *36*, 525 – 529. [6] Chambers, J. E. (1999) *Mon. Not. RAS*, *304*, 793-799. [7] Housen K.R. et al. (1983) *JGR*, *88*, 2485 – 2499. [8] Artemieva N.A. & Shuvalov V.V. (2008) *Solar Syst. Res.*, *42*, 329 – 344. [9] Holsapple K.A. (1993) *Ann. Rev. Earth Planetary Sci*, *21*, 333 – 373.

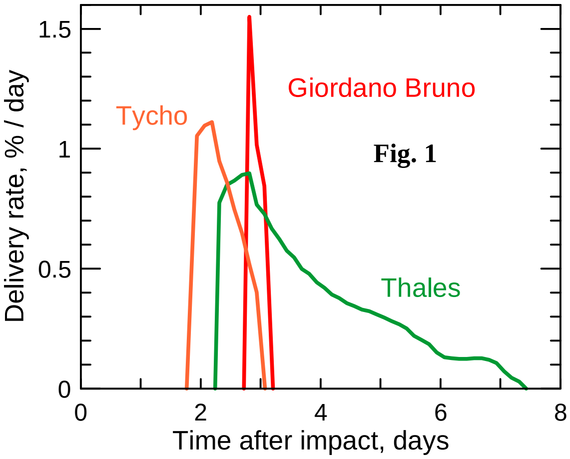

Fig. 1

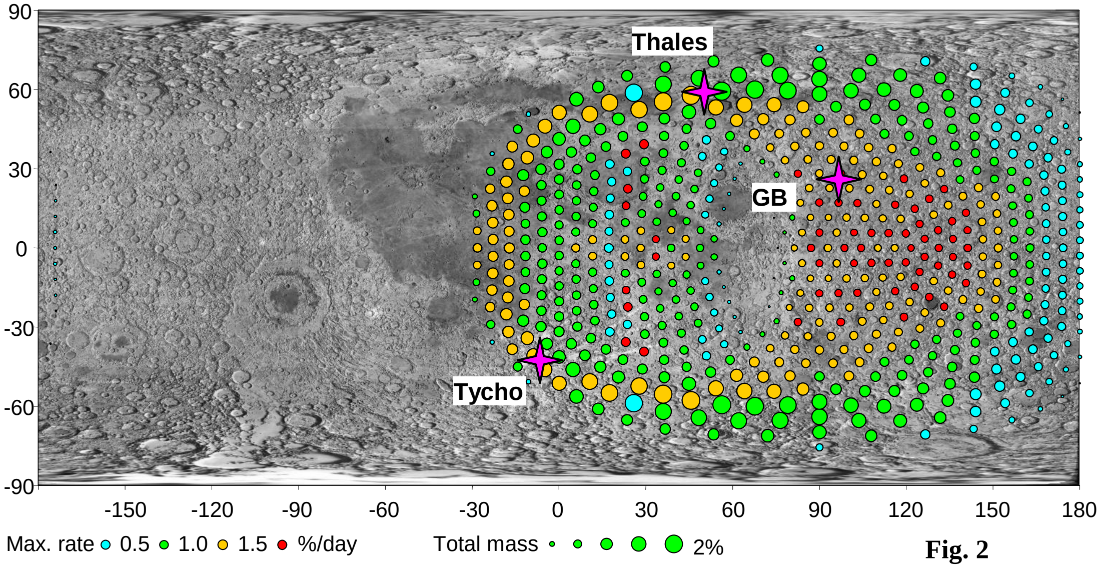

Fig. 2