A MOTH-EATEN BLANKET: RE-IMPACTING DEBRIS PUNCTURED HOLES IN THE EARLY LUNAR CRUST.

Alan P. Jackson[1], Viranga Perera[2] and Travis S.J. Gabriel[1], [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA, [2]Purdue Polytechnic Institute, Purdue University, West Lafayette, IN, USA. Email: alan.jackson@asu.edu

Introduction: It is widely considered that a deep, global Lunar Magma Ocean (LMO) existed on the Moon shortly after its formation. Direct geochemical evidence for the existence of the LMO comes from the ferroan anorthosite (FAN) samples returned from the lunar surface by the Apollo missions. The preferred formation scenario for these FANs is via fractional crystalisation of the LMO, in which they would float to the surface via density separation [e.g., 1]. Moreover, the existence of an LMO is expected on thermal grounds. The Moon likely formed in the aftermath of a giant impact between the proto-Earth and another proto-planet [e.g., 2, 3]. The circum-terrestrial disk of debris would have been hot (2500-5000 K) [3], and the Moon is likely to have accreted rapidly, acquiring most of its mass within a month to a year after the impact [e.g., 4], leaving it initially very hot and likely fully molten.

Over time the LMO cooled and solidified. Initially this proceeded rapidly, but once buoyant anorthosite began to form and accumulate at the surface, building the primordial lunar crust. The thermal blanketing effect of this overlying material could slow the cooling rate of the LMO substantially [e.g., 5, 6]. The timing of the solidification of the LMO provides the starting point for lunar geochronology, which serves as a key temporal tie-point for our solar system. Having an accurate model of this solidification process is thus important in establishing consistent relationships in lunar sample ages and putting them into context with other prominent solar system formation events.

The Moon, and the LMO, does not evolve in isolation however. In the Canonical model of Moon-formation about 10^{23} kg, or 1.3 lunar masses, of material escapes onto heliocentric orbits in addition to the circum-terrestrial disk of material that coalesces to form the Moon [7]. This heliocentric debris is injected directly onto planet crossing orbits and collides with the terrestrial planets at a high rate, especially Earth and the newly formed Moon. *In total the Moon receives over 10^{20} kg of impactors, which would have had catastrophic implications for the forming anorthositic crust, potentially altering the cooling rate of the Moon.*

Perera et al. [6] conducted the first investigation of how re-impacting debris could influence the cooling of the LMO in terms of two effects, the creation of holes in the insulating lunar flotation crust, and the conversion of impact kinetic energy into heat in the LMO. They parameterised hole creation efficiency in terms of a factor k, the impactor mass required to generate 1 m^2 of hole, and the conversion of kinetic energy in terms of a simple conversion fraction, λ_{KE}. The change in LMO solidification time as a function of these two parameters can be seen in Fig. 1, taken from [6]. Note that this figure does not include heating in the LMO due to tides or the decay of radionuclides.

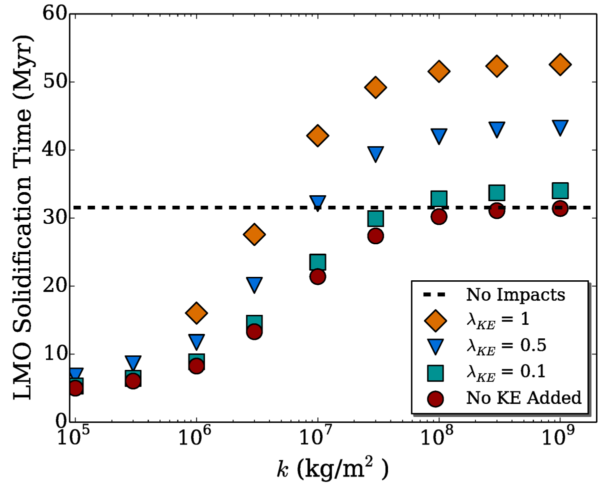

Figure 1: LMO solidification time as a function of the hole opening efficiency, k, for different assumptions of the kinetic energy conversion efficiency, λ_{KE}. The black dashed line corresponds to the fiducial case in which impacts are neglected. From [6], their Fig. 7.

The work of [6] clearly showed that the influence of re-impacting debris on the cooling of the LMO can be substantial, and can result in either a decrease or an increase in the time for complete solidification, depending on the value of k and λ_{KE}. Values of k below around 3×10^6 kg/m^2 will always lead to a decrease in the solidification time, whereas at higher values of k the solidification time can increase if λ_{KE} is high enough.

In this work, we specifically examine the process of impact crater and hole production in various LMO layering scenarios in order to determine the likely range of k, allowing us to understand the influence re-impacting debris on LMO solidification timing.

Methods: We use the well-established iSALE shock physics code to simulate impacts into the flotation crust over the LMO [8, 9, 10]. We perform over 240 simulations with impactors ranging from 0.1-30 km in diameter, impact velocities from just above escape velocity to 15 km/s, and a crust thickness between

1–40 km. Our Moon is constructed with a dunite mantle and a granite crust using the ANEOS equation of state [11]. These material choices satisfy our two primary criteria; that the solid crust is less dense than the liquid mantle, and that the crust has a higher melting temperature than the mantle ([12] found that the exact equation of state used is less important than the relative densities). The temperature within the liquid magma layer follows an adiabatic gradient such that mantle temperature crosses the melting temperature-pressure curve at a depth matching that in [5] for the corresponding crust thickness. Impacts are simulated in a half-space (2-D axisymmetric) setup.

Results: We identify 2 primary categories of impact outcomes, cratering and penetrating, separated by whether or not the impactor breaches the base of the crust. We further divide penetrating outcomes into 'partial' and 'complete' on the basis of whether or not inflow of crustal material after the collapse of the transient cavity is able to cover the exposed magma.

For all penetrating impacts we construct a characteristic hole opening energy, $E_{\mathrm{HO}} = \pi \rho g R_{\mathrm{thin}}^2 d_{\mathrm{cr}}^2$, where ρ is the density of the crust material, g is the (lunar) acceleration due to gravity, R_{thin} is the radius within which the crust is thinned to less than 95% of its initial value and d_{cr} is the initial crust thickness. This is thus the energy required to lift a circular plate of crust material with radius R_{thin} and thickness d_{cr} by a distance equal to its thickness. Comparing E_{HO} with the impact kinetic energy we find a very close to linear correlation with $E_{\mathrm{HO}} \approx 0.05 E_{\mathrm{k}}$. We further find that for complete penetrations a $\approx$13 d_{cr}-wide region of thinned crust surrounds the central pool of exposed magma.

Combining our relations for E_{HO} and the rim of thinned crust we can determine the size of the pool of exposed magma for any desired impactor. Integrating over the expected size-distribution of impactors we can then determine the value of k for any impact velocity and crust thickness, which we show in Fig. 2. The mean impact velocity is around 5 km/s initially, rising to around 11 km/s at 10 Myr, and finally to around 17.5 km/s by 100 Myr after the Moon-forming impact. The result of this is that k starts off low and increases over time, and because of the shape of the contours on Fig. 2 spends the longest period of time close to $k = 10^7$. Fig. 1 shows that this lands us in the region where λ_{KE} is important in determining whether the LMO solidification time is increased or decreased, and establishing the value of λ_{KE} will thus be the subject of our next work. While a complete picture of the LMO solidification time must wait for future work on λ_{KE}, it is clear that re-impacting debris has a strong effect on the early history of the Moon and cannot be neglected if we are to accurately model this key anchor in solar system chronology.

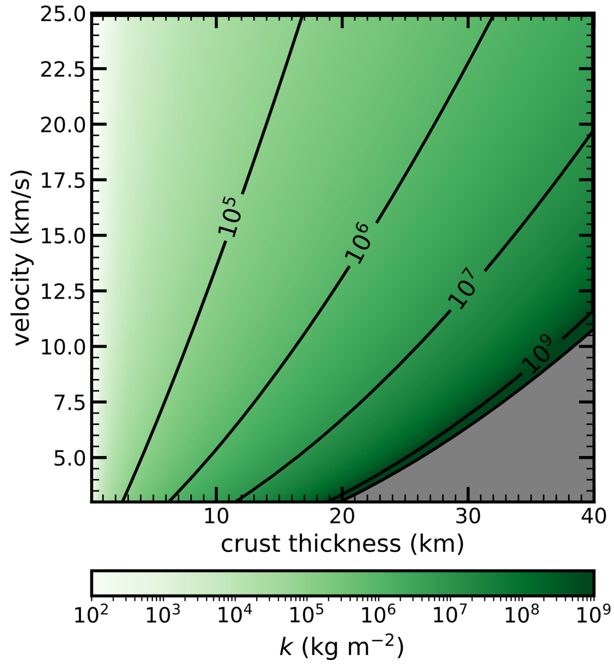

Figure 2: Green shading shows the average hole opening efficiency, k, integrated the expected impactor size distribution as a function of crust thickness and impact velocity. The grey shading shows the region in which the largest (100 km) impactors we consider are not capable of producing a complete penetration.

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