EFFECT OF RE-IMPACTING DEBRIS ON THE SOLIDIFICATION OF THE LUNAR MAGMA OCEAN.

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Introduction: Previous works have used both geochemical analyses and thermal models to argue that the early Moon possessed a Lunar Magma Ocean (LMO). The LMO idea was proposed after geochemical analyses of Apollo samples identified ferroan anorthosite (FAN) rock fragments [1]. It is likely that those fragments are from the primordial lunar crust, which itself formed from the amalgamation of anorthositic rocks that floated to the surface after fractionally crystallizing out of the LMO [2]. Complementary to geochemical work, the LMO is expected from a thermal modeling perspective as well. The Moon likely formed in the aftermath of a giant impact between the proto-Earth and another planetary body [3], thus a predominantly molten early Moon is expected for two reasons. Firstly, the high-energy impact event would have produced hot debris from which the Moon coalesced (disk debris temperatures after the impact ranging from 2,500 to 5,000 K [4]). Secondly, the Moon would have rapidly acquired most of its mass (within a month to a year after the impact [e.g. 5]).

Though geochemical analyses and thermal models are complementary when arguing for the LMO, the two approaches generally disagree on the timescale over which the LMO solidified. While geochemical analyses give timescales ranging from about 100 to 254 Myr [e.g. 6], geophysical models range from 10 to nearly 300 Myr [e.g. 7]. Generally, solidification is prolonged to $\sim$ 100 Myr in thermal models by utilizing additional heat sources such as tidal heating [e.g. 8]. Nevertheless, some of have challenged that the $\sim$ 100 Myr geochemical timescales include later melting events and thus are not representative of the LMO solidification time [9]. Since there is disagreement in estimates of the LMO solidification time, further work is necessary to reconcile geochemical analyses and thermal modeling timescales.

To support that effort, we developed a thermal model that iteratively solidifies volume segments of the LMO while releasing thermal energy through the surface. Our work differs from previous work in that we incorporate the effect of impacts onto the Moon by debris that escaped after the Moon-forming giant impact. We show that re-impacting debris can either expedite or prolong LMO solidification in a significant manner.

Re-Impacting Debris: As mentioned, the Moon likely formed from debris produced in a giant impact. Not all of the debris was incorporated into the Moon however, since some had sufficient speed to escape the Earth-Moon system. About 10^{23} kg ($\sim$ 1.3 lunar masses) of debris is estimated to have escaped onto heliocentric orbits [10] for the Canonical Moon formation scenario (see [4]). Extensive analysis of the dynamical evolution of that debris using N-body simulations have shown that a significant fraction would have returned over a period of 100 Myr and impacted the Moon [11]. Following that work, here we utilize results of an improved N-body simulation for our thermal model.

Overview of LMO Solidification: It is convenient to divide LMO solidification into two parts: prior to and after the start of anorthositic rock formation. The first part runs from the beginning of solidification to the point at which $\sim$80% of the initially 1000 km deep LMO is solidified, but it lasts for a short time period ($\sim$ 100 to 1,000 yr depending on LMO surface conditions). This rapid cooling is due to a high thermal flux through the surface. The solidification of the remaining 20% of the LMO lasts much longer and thus dominates the LMO solidification time (10 Myr according to [7]). Once anorthositic rocks form and float to the surface, the primordial lunar crust starts to form. That conductive lid appreciably lowers the thermal flux through the surface.

Re-impacts Prolonging or Expediting LMO Solidification: Re-impacts can expedite LMO solidification by puncturing holes into the lunar crust and thus increasing the thermal flux through the surface. They can also prolong LMO solidification by transferring their kinetic energy as thermal energy. Since hole puncturing is dependent on a number of factors such as impactor velocity, crustal thickness and strength, we simplified our model by using a conversion factor k (with units of kg/m^2) that converts incoming impactor mass flux from N-body results to an area of holes produced during a given timestep. Large k values (e.g. 10^9 kg/m^2) would mean that though impactors strike the Moon, they only minimally puncture holes, while small k values (e.g. 10^5 kg/m^2) would mean that a small impactor mass would produce a very large area of holes. Both

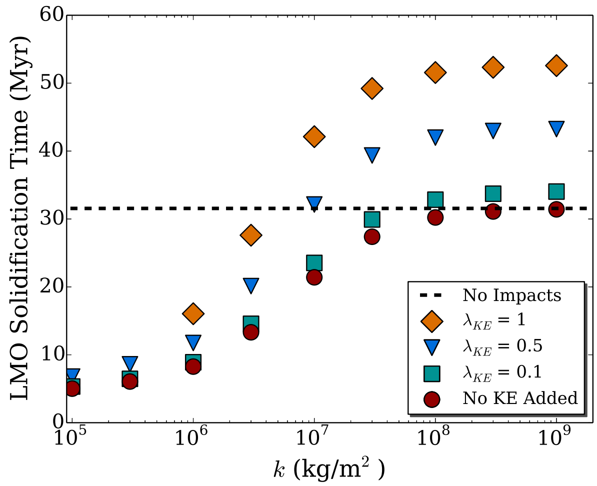

Figure 1: LMO solidification time as a function of k and λ_{KE}. The no impacts solidification time is shown with a dashed black line for reference.

large values and small values are somewhat unrealistic, but serve as upper and lower bounds. We expect that $k \sim 10^7$ kg/m^2 is likely to be typical.

The conversion of impactor kinetic energy into thermal energy in the LMO again is dependent on a number of factors. Thus, we simplify that process by using an efficiency factor (λ_{KE}). $\lambda_{KE} = 1$ corresponds to complete conversion of impactor kinetic energy to thermal energy in the LMO, while $\lambda_{KE} = 0$ would mean that none of the impactor kinetic energy is imparted as thermal energy. Again, much like k, the upper and lower values of λ_{KE} are unrealistic but they serve as bounds.

Fig. 1 shows how k and λ_{KE} affect LMO solidification time. In the no impacts case, the LMO solidifies in about 30 Myr. With no kinetic energy conversion ($\lambda_{KE} = 0$) impacts always reduce the solidification time, with more intense hole production (lower k values) leading to faster solidification. When $\lambda_{KE} > 0$ and the intensity of hole production is low, LMO solidification takes longer than the no impacts case. If hole production is sufficiently intense it can overcome the additional thermal energy input and for $k \lesssim 10^7$ kg/m^2 solidification is faster regardless of the value of λ_{KE}.

Reconciling Geochemical Analyses with Thermal Models: If we assume geochemical estimates of $\sim$ 100 Myr for LMO solidification time are accurate, then Fig. 1 shows that while certain re-impact scenarios may prolong LMO solidification it is not sufficient. Certain impact scenarios would make the discrepancy worse by reducing the LMO solidification time. In Fig. 2 we show the average additional heating (e.g. from tides) necessary to prolong LMO solidification for different k and λ_{KE} values. When hole production is not very intense, a moderate amount of additional heating is able to prolong LMO solidification enough to be consistent with geochemical analyses. However, for more intense hole production scenarios the amount of additional heating required to significantly extend the solidification time is greater than 10 TW, more than can reasonably be provided by tidal heating.

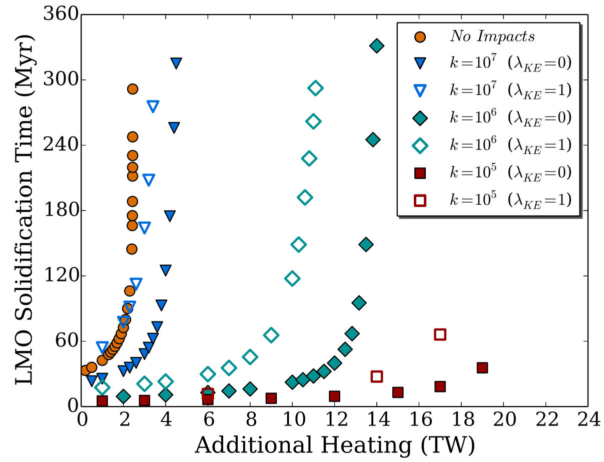

Figure 2: LMO solidification time as a function of additional constant heating. The without impacts case is shown with orange circles. The with impacts and with $\lambda_{KE} = 0$ cases are shown with filled markers: blue triangles ($k = 10^7$ kg/m^2), dark cyan diamonds ($k = 10^6$ kg/m^2), and dark red squares ($k = 10^5$ kg/m^2). The corresponding $\lambda_{KE} = 1$ cases are shown with unfilled markers.

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