EPSC Abstracts
Vol. 15, EPSC2021-548, 2021
https://doi.org/10.5194/epsc2021-548
Europlanet Science Congress 2021

Crystal Distribution in a Solidifying Lunar Magma Ocean

Nikolas Wiesner[1] and Sabrina Schwinger[2]
[1]German Aerospace Center (DLR), Planetary Physics, Berlin, Germany (sabrina.schwinger@dlr.de)
[2]TU Berlin, Berlin, Germany (nikolas@physik.tu-berlin.de)

Introduction:

During its early history, the Moon experienced a phase of planetary-scale melting that is commonly referred to as the Lunar Magma Ocean (LMO). Progressive crystallization of the LMO lead to differentiation of the lunar interior into a crust and a stratified mantle.

The composition of the crystallizing solids strongly depends on the degree of crystal fractionation. However, the degree of crystal fractionation in the magma ocean and its evolution with time is still poorly constrained since it depends on multiple factors, including the initial thermal state of the LMO, the ability of the magma to suspend crystals by vigorous convection or the kinetics of crystal growth and dissolution during transport in the LMO and the resulting distribution of crystals in the LMO.

In this study we combine multiple modeling approaches to investigate the distribution of crystals in a solidifying magma ocean and the evolution of the crystal budget during LMO solidification.

Methods:

In our model we assumed that two processes contribute to the total crystal budget of the early LMO: the formation of crystals in regions where the temperature drops below the liquidus and the introduction of solid material by impacts.

Crystal formation in the LMO: We assumed an initially 1350 km deep LMO that progressively cools from its liquidus temperature. The thermochemical evolution of the solidifying LMO was modeled using the phase equilibria software packages alphaMELTS and SPICES [1,2,3]. The results were used to calculate the temperature and composition dependent viscosity of the evolving magma as well as the solidus and liquidus temperatures at different stages of LMO evolution.

We used the convection code GAIA [4] to model the temperature distribution in the convecting LMO at distinct stages of LMO evolution. We assumed that the time scale required for significant changes in the thermochemical properties is many orders of magnitude larger than the relaxation time of the convecting magma, so that the convection is in a steady state at any given stage of the LMO evolution. Therefore, we modeled each stage of the evolution separately, using the results from our solidification model to define the initial temperature profile and the physical properties of the LMO.

By comparing the steady state temperature distribution with the solidus and liquidus temperatures of the LMO, we determined the local equilibrium crystal fractions for each grid point.

Crystal introduction by impacts: We assumed that the LMO is impacted by a population of spherical impactors with varying initial sub-solidus temperatures of 0 K and 1360 K. As suggested by [5], we assume the size distribution of the impactor population to be that of a self-similar collision cascade and impactors to be of bulk Moon composition. The impact velocity was not considered as a model parameter and was assumed not to affect the properties and sinking behavior of the impactors.

Individual impactors were assumed to sink with velocities depending on their sizes and densities as well as the density and viscosity of the surrounding magma. This velocity and the LMO depth were used to calculate the residence time of the impactors in the LMO before reaching the LMO bottom.

We applied a 1D heat diffusion model to calculate the temperature distribution in the sinking impactor. Thereby we assumed time dependent boundary temperatures depending on the radial position of the impactor during sinking. Solidus and liquidus temperatures of the impactors as well as the latent heat of melting were calculated with alphaMELTS and used to calculate the degree of melting of the impactor.

Results:

We found that the temperatures in the early LMO are close to the mean temperature with deviations of only a few K due to vigorous convection. The local deviations from the mean temperature increase as the LMO evolves, since the liquid viscosity increases due to the compositional evolution and progressive cooling of the liquid.

Subliquidus temperatures are reached only within a region close to the LMO bottom. The thickness of this crystal bearing region decreases as the LMO solidifies.

Nevertheless, the shallower regions are not completely free of crystals due to the introduction of impacting material. Our results indicate that impactor fragments with a size of more than ~1m will reach the bottom of the LMO without melting completely.

Discussion:

The preliminary results of our models indicate that both the growth of crystals from the magma ocean liquid and the introduction of solid material from impacts contribute to the crystal budget of the LMO. This has implications for the magma ocean dynamics as the crystal budget influences magma viscosity.

The surface of impacting solid material reaching the crystallization region also provides nucleation sites that facilitate the heterogeneous nucleation of crystals. Heterogeneous nucleation on pre-existing solid aggregates requires less undercooling than homogeneous nucleation from the LMO liquid. Thus the presence of impacted material might lead to an increased average size of crystals or crystal aggregates in the LMO and hence facilitate the fractionation of solid material from the LMO.

To allow a quantitative estimate of the influence of impacts on the crystal budget in the early LMO, future iterations of the model will account for the effect of impactor fragmentation on the size distribution of sinking material, initial velocities of the fragments after impact and initial heating of the fragments by shock.

References:

[1] Smith and Asimow (2005), G^3, 6.2.

[2] Davenport (2013), Planet. Sci Res. Disc. Report 1, 173.

[3] Schwinger and Breuer (2021), https://arxiv.org/abs/2104.06847.

[4] Hüttig et al. (2013), PEPI 220, 11-18.

[5] Perera et al. (2018), GJR: Planets, 123(5), 1168-1191.