Numerical experiment on the formation process of barred-olivine texture in chondrules: Effect of compositional change due to evaporation

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Primitive meteorites contain mm-sized spherical grains composed mainly of silicates. These are called chondrules, which are thought to have been formed by the heating and melting of mm-sized dust aggregates by some mechanism in the early solar system, and then were formed into a spherical shape by surface tension, followed by rapid cooling and solidification. The solidification texture inside a chondrule is thought to reflect the thermal history experienced by the chondrule, and many dynamic crystallization experiments have been conducted to investigate the thermal history that can reproduce the texture. The results of these experiments are summarized as "observational constraints," and the theoretical goal of chondrule studies has been to find a formation process that satisfies the observational constraints. However, no formation process that satisfies all of the constraints has been proposed, and the causes of chondrules are still under debate.

One of the reasons why the chondrule formation process is unresolved is that the solidification process of molten chondrules is not well understood theoretically. For example, the solidified texture called barred-olivine (BO) is thought to have formed by rapid cooling from a totally melted droplet [e.g., 1]. The olivine crystal in the BO texture shows a characteristic morphology with many parallel bar patterns (bars) and spherical patterns (rims) surrounding the entire bar pattern, and they are connected with aligned crystallographic orientations. It is not clear how an olivine crystal with this characteristic shape grew inside the rapidly cooling molten droplet. Numerical calculations of the olivine crystal growth process inside a rapidly cooling droplet have been attempted [2,3], but they assumed a single-component system and are not directly applicable to a multi-component system such as chondrules. Since the dynamic crystallization experiments do not always faithfully mimic the space environment, it is important to understand the chondrule solidification process itself theoretically in order to discuss the chondrule formation process on the basis of the results of the experiments.

In this study, we developed a numerical model of the crystal growth process of olivine in multi-component silicate droplets to theoretically elucidate the chondrule solidification process. The model is based on the quantitative phase-field model for MgO-FeO-SiO_2 ternary system [4]. A fully molten droplet was considered to be a two-dimensional circle (the reason why it was not made into a three-dimensional sphere was due to computational cost), and an olivine seed crystal was placed at its surface. We also considered the compositional change of the droplet interior due to the evaporation of FeO from the surface. The results suggest that evaporation may play an important role in the formation of the rim. The compositional change due to evaporation raises the liquidus temperature and increases the effective undercooling near the droplet surface. The seed crystal grows rapidly along the droplet surface, which becomes the rim. Simultaneously, numerous branches are generated on the sides of the rim, which elongate toward the interior of the droplet while remaining nearly parallel to each other. These become bars. The generation of branches is due to a physical mechanism called interfacial instability, which results from the elemental partitioning between the growing crystal and the melt. The rim and bar formation process shown in the present calculations can naturally explaine the feature that the crystallographic orientations of both are aligned.

Reference: [1] Rubin, E. R. et al., 2023, *Meteorit. Planet. Sci.* 1-15. [2] Miura, H. et al., 2010, *J. Appl. Phys.* **108**, 114912. [3] Miura, H. et al., 2011, *Earth Planets Space* **63**, 1087. [4] Miura, H., 2023, *Materialia* **31**, 101860.

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