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Recalescence during chondrule melt crystallization and formation of the solidification textures

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The chondrule formation environments in early solar nebula have been controversial for the last few decades. It is considered that the most important factors for forming the chondrule solidification textures are the peak temperature of chondrule melt droplet and the cooling rate during solidification. The proper conditions have been obtained from crystallization experiments and comparisons of the solidification textures with that of natural samples [1]. However, the understandings of crystallization processes from traditional experiments are still in speculations because in-situ observations of chondrule melt crystallization have not been carried out. A few examples of the in-situ observations were reported by using freely-falling methods and levitation methods [2-4]. These in-situ observations in which single-component melt droplets were used as starting materials showed that the homogeneous nucleation occurs at very large supercooling (about a few hundred K or more), and never at lower supercoolings. After nucleation, however, the crystallization speed is so fast that it took only about less than a few seconds to finish the entire process of crystallization. In addition, the temperature of the droplet increases as it crystallizes, which is due to the release of latent heat of crystallization and observed as instantaneous increase of thermal radiation from the droplet surface (recalescence).
The purpose of our study is to elucidate the fundamental processes of chondrule melt crystallization by using numerical simulations. The understandings of the fundamental processes would be a great help to constrain the chondrule formation environments more clearly. Here, we numerically calculate the crystallization of a supercooled chondrule melt droplet, in which the nucleation starts from a certain point on the melt surface.
For the simulations, we adopt the phase-field model [5], which takes into account the following physical processes; local temperature increase associated with crystallization, unsteady thermal diffusion, and crystal growth speed depending on supercooling at crystal-melt interface. We consider the section of chondrule melt droplet as the computational domain and solve the phase-filed equations with two-dimensional uniform square meshes. We used the physical properties of pure forsterite (Mg_2SiO_4) melt (single-component) for simplicity. Our numerical simulation reproduced extremely rapid crystallization as is revealed in the levitation experiments. In addition, as the crystal grows from the droplet surface to its interior, the crystal-melt interface showed very complex morphology. The complex morphology is a result of morphological instability, which is caused during crystal growth in "negative" temperature gradient (Mullins-Sekerka instability) [6]. It was also found that the crystallization patterns depend on supercooling and cooling rate at droplet surface significantly. Our numerical simulations strongly suggest that the recalescence plays an important role for crystallization of a largely-supercooled melt droplet under levitated conditions.

References:
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