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Rapid cooling of chondrule to reproduce olivine bars observed in barred olivine chondrules

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Chondrules are millimeter-sized and spherical-shaped crystalline grains consisting mainly of silicate material. Since chondrules occupy about 80 vol.% of chondritic meteorites in abundant cases, they must have great information about the early history of our solar system. They are considered to have formed from molten droplets about 4.6 billion years ago in the solar nebula; it is believed that they melted and cooled again to get solidified in a short period of time. They have various solidification textures that record the solidification process. Barred olivine (BO) chondrules show a unique texture characterized by parallel set(s) of olivine bars in a thin section. BO chondrule usually has an olivine crystal, which is termed as rim, which covers the chondrule surface. This olivine rim has the same crystallographic orientation as inner olivine bars, which connect to the rim. It is considered that the crystallographically continuous structure was formed by morphologic instability during olivine growth, like dendritic crystals. However, initial process of the morphologic instability that produces the olivine bars has not been investigated in details.

We investigated the initial process of formation of BO texture based on numerical simulation of solidification of chondrule melt. The thermodynamically consistent phase-field model for a binary alloy based on the entropy functional is adopted here. We adopted Mg_2SiO_4-Fe_2SiO_4 binary system in which only olivine is considered as a solid phase. We carried out a numerical simulation of a molten olivine droplet solidifying from a platy seed crystal at droplet surface. Under an extremely rapid cooling condition, in which the cooling rate is 5000 K/s, the platy seed crystal overgrew keeping its flat interface at the beginning of solidification, and then changed to cell-like pattern due to morphological instability. The initial stage before the instability can be considered as the formation of olivine rim, and the cell-like pattern as that of olivine bars. In this case, the average width of bars is about 5 micrometer in numerical result, which is comparable to that observed in natural BO chondrules ranging from 5 to 100 micrometer. If we consider that the bar width is proportional to a root of the cooling rate, the required cooling rate to reproduce 100 micrometer thickness is evaluated as 12.5 K/s = 45000 K/hr, which is much faster than the canonical value of 1000 K/hr inferred from traditional experiments. We also found that the rim and olivine bars showed zoning profile in Fe/(Mg+Fe) value, which was similar to that of laboratory-synthesized BO chondrules.

Our numerical simulation of solidification of chondrule melt suggested that the cooling rate should be much faster than that inferred from traditional experiments to produce olivine bars of 5 ? 100 micrometer in width such as observed in natural BO chondrules.

Keywords: chondrule, solidification texture, crystal growth, zoning profile