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For understanding chondrule formation: crystallization process of mm-sized levitated magma droplet in space

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Chondrules are millimeter-sized, once-molten, spherical-shaped grains consisting mainly of silicate material and are one of the significant components of primitive meteorites. They are considered to have formed from chondrule precursor dust particles about 4.5 x 10^9years ago in the solar nebula; it is believed that they were heated and melted through flash heating events and cooled again to get solidified in a short period of time. Chondrules occupy about 80 vol% of chondritic meteorites in abundant cases, so it can be said that they are one of the main components of rocks in our solar system.

The chondrule formation is, as it were, "crystallization process of a mm-sized levitated magma droplet." Under levitated conditions (no contact surface), a completely-molten droplet hardly crystallizes because the heterogeneous nucleation at contact surfaces does not take place. It requires some induction time for homogeneous nucleation, so the droplet becomes largely supercooled by rapid cooling.

In order to understand the crystallization process of chondrule melt, we have carried out crystallization experiments and in-situ observation of the crystallization processes by using levitation methods. Our experiments with melt droplets of forsterite (Mg_2SiO_4) composition as the starting material showed that the homogeneous nucleation occurs at very large supercooling (about a few hundred K or more). After nucleation, however, the crystallization speed is so fast that it took only about 0.1 seconds to finish the entire process of crystallization. In addition, the temperature of the droplet increases as it crystallizes. This is due to the release of latent heat of crystallization and observed as instantaneous increase of thermal radiation from the droplet surface (recalescence). It was found that the recalescence occurs at a spot on the surface at first, then spreads to the whole surface. This means that during crystallization there is a very large temperature difference of about a few hundred K in a mm-sized droplet.

How does the recalescence affect the crystallization process of chondrule melt? To answer this question, we carried out numerical simulations of chondrule melt crystallization. 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). Various crystallization patterns emerge in droplet depending on the crystallization conditions; nucleation supercooling and cooling rate of droplet. At a certain condition, we reproduced the crystallization pattern very similar to solidification textures of natural chondrules. From our numerical simulation, it was found that the steep temperature gradient in a highly supercooled droplet plays an important role to generate solidification texture of chondrules.

Our recent researches on peculiar features of crystallization under levitated conditions propose a new scenario of chondrule formation, which is significantly different from the traditional ones. The emphasis of our studies is to address the crystallization process of chondrules based on in-situ observations and numerical simulations. To start with, we have considered a single-component droplet to understand the most basic process, but actual chondrule melt is multi-component, so we have to extend our studies to the multi-component system in the future. What is the difference on the crystallization process between space and on the Earth? How does the new understanding modify the chondrule formation scenario? To answer these questions, one would require not only the traditional ways in geochemistry and earth science, but also new methods and approaches that have been never used before.

Keywords: chondrule, crystallization experiment, levitation method, in-situ observation,
numerical simulation, recalescence