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Crystallization from a melt sphere: chondrule formation from a supercooling liquid

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The crystallization of liquid is determined by two processes, i.e., nucleation process and growth process of crystalline nuclei. The nucleation rate is sensitive to the interfacial energy between liquid and crystal and the growth rate of the crystal is determined by the activation energy of self diffusion [1]. The data of the interfacial energy and the activation energy are then indispensable to estimate the time scale of the crystallization. In this study we evaluate the interfacial energy between liquid and crystal and the activation energy by comparing a theoretical model of crystallization with the experiments by gas jet levitation method.

Nagashima et al. [2] investigated the crystallization from silicate liquids by the experiment using a gas jet levitation system in relation to the formation of chondrules, which are small silicate spherules found as a major constituent in primitive meteorites. They observed the time variation of temperature of a liquid sphere of forsterite (Mg_2SiO_4) and enstatite ($MgSiO_3$) compositions, which are the primary mineral components in the meteorites. In the cooling, crystal nuclei form and grow in the liquid and the sphere is heated by the latent heat of crystallization. They obtained the crystallization time when the temperature increases sharply due to the release of latent heat and found that the large supercooling is required for the crystallization of forsterite liquids. They also showed that the crystallization of enstatite is more difficult than that of forsterite: a glass of enstatite composition forms under the same cooling rate as forsterite experiment.

We present a theoretical model of crystallization of a liquid sphere taking into account nucleation, growth of crystalline nuclei, and the release of latent heat due to the crystallization. We suppose initially a completely melted sphere, which cools due to the radiation and gaseous collisions under the assumprion that the sphere is isothermal. We obtain conditions for three states in the cooling of the melt sphere, i.e. crystallization near the melting point, crystallization in the supercooling liquid, and glass formation, found in the experiments. For the small values of the interfacial energy and the activation energy, there are two status of the crystallization: the crystallization near the melting point and that in the supercooling liquid. Otherwise the crystallization does not occur and the glassy sphere forms. We also obtain the interfacial energy and the activation energy of forsterite composition by comparing the time variation of the temperature between the model and the experiments.

Using the evaluated values of the interfacial energy and the activation energy, we can predict the time variation of the temperature for various cooling rates. We introduce an example in relation to the formation of the chondrules. In the experiments, the cooling rate was mainly determined by the cooling due to the gas jet. But the actual cooling rate is smaller than the experiments because the cooling due to the gaseous collision is not effective in the protoplanetary disk where the chondrules form. In the protoplanetary disk the dust cools only due to the radiation. Our results suggest that the forsterite chondrules form from the supercooling liquid.

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