Cooling Rate of Chondrule Estimated from Compositionally Zoned Olivine

Hitoshi Miura[1] and Tetsuo Yamamoto[2]

[1]*Nagoya City University, Japan,* [2]*Kobe University, Japan*

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 rich information on 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. During the cooling process, some crystalline phases such as olivine and pyroxene grew from the bulk chondrule melt to form phenocrysts, and the residual melt solidified to form mesostasis. The cooling rate affects the size, morphology, and compositional zoning of phenocrysts, so many authors have investigated conditions for chondrule formation by crystallization experiments. However, the crystallization process has not been understood clearly because of a lack of theoretical considerations.

Compositional zoning in chondrule phenocrysts reflects the crystallization process from a molten chondrule melt droplet. We modeled the growth of phenocrysts from a silicate melt and proposed a new fractional crystallization model that provides a relation between the zoning profile and cooling rate. In our model, we took elemental partitioning at growing solid-liquid interface and time-dependent solute diffusion in liquid into consideration. We considered olivine as a model material because its thermodynamical properties are described by an ideal solution. In addition, we assumed equilibrium at the interface, namely, the concentrations at the interface are equal to equilibrium ones at a given temperature. We carried out numerical simulations of the fractional crystallization in one-dimensional system. The numerical simulations revealed that under a constant cooling rate the growth velocity of solid increases exponentially with time, and a linear zoning profile forms in the solid as a result. We obtained an analytic formulae of the zoning profile, which reproduces the numerical results for wide ranges of crystallization conditions. This analytic formulae would be a useful tool to estimate the cooling rate from compositional zoning. We applied the analytic formulae to the linear zoning profile in overgrown olivine phenocrysts and estimated the cooling rate to be $\sim 10^3$ K s^{-1}, which is orders of magnitude faster than that estimated previously from furnace-based experiments. Such high rate is consistent with the chondrule having cooled by radiation into ambient cool space.