Cooling conditions of chondrules constrained from metal-sulfide assamblages

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Chondrules are millimeter to sub-millimeter sized silicate spherules that formed during localized and transient high-temperature events in the early solar system. It is important to reveal the thermal history of chondrules to constrain the heating mechanism of chondrules.

Dynamic crystallization experiments to reproduce textures of silicate portion of chondrules have suggested that chondrules were heated up to peak temperatures of 1800-2200 K and cooled at the rate of 5-1000 K/h (e.g., Tsuchiyama et al., 1980). Such estimated cooling rates are, however, those at temperatures above the solidus of silicates, and little is known for cooling rates at lower temperatures, which will provide additional important constraints on formation environments of chondrules.

In this study, in order to constrain cooling rates of chondrules below the silicate solidus, we focus on textures of metallic iron-troilite assemblages, which would have been melted immiscibly with silicates and may have existed partly as a melt even at temperatures lower than the silicate solidus. We performed crystallization experiments of Fe-Ni-S melt and compared textures of metal-troilite assemblages produced in experiments with those in chondrules.

We observed 114 metal-troilite grains within 34 chondrules from Bishunpur (LL3.1), one of the least metamorphosed ordinary chondrites, by FE-SEM equipped with EDS. The area and roundness of the grains were determined by image analyses. The bulk compositions of an assemblage were roughly estimated based on modes of metal and troilite. Metal-troilite assemblages larger than several tens microns tend to be irregular because they shaped by silicate phenocrysts especially when they contain sulfur contents close to the Fe-FeS eutectic compositions. This implies that such larger metal-troilite assemblages existed as a melt and solidified at lower temperatures than the silicate solidus and that such textures record the cooling history of chondrules at temperatures below the silicate solidus.

Crystallization experiments of Fe-Ni-S melt were performed in sealed, evacuated silica tubes. Natural pyrrhotite and Fe-Ni metal were mixed with different mixing ratios and were pressed into pellets. The pellets were placed in a silica tube and sealed after evacuating a tube with a rotary pump. The tubes were kept at 1050oC for 0.5 hour, and cooled to 350oC linearly at the rates of 100, 10, or 3 K/h.

Pellets containing only pyrrhothite show a small amount of metallic iron grains after experiments, indicating that a small amount of sulfur evaporated. However, evaporated sulfur is estimated to be only a few %, and the bulk compositions of pellets would not change significantly.

Eutectic solidification textures were observed for samples with the Fe-FeS eutectic composition and those close to the Fe-FeS eutectic but containing about 4 wt% of nickel. The spacing between metallic iron rods seems to be dependent on the cooling rate: average spacings are 11+/-3, 19+/-9, and 29+/-9 micron for cooling rates of 100, 10, and 3 K/h, respectively. Note that a quenched Fe-FeS eutectic melt also show the eutectic solidification texture with average spacing of about 1-2 micron (Tachibana and Tsuchiyama, 1998), which is much smaller than those observed in this study. Samples with compositions containing more iron and nickel did not clearly show such textures, but contained about 100-micron-sized metal spherules.

Many of metal-troilite assemblages within chondrules observed in this study, especially several micron-sized grains, did not show clear textual evidence for the eutectic solidification of the metal-sulfide melt. This suggests that cooling rates of chondrules may have been lower than 100 K/h at about 1000oC. The estimated cooling rate at temperatures lower than the solidus of chondrule silicates seems to be consistent with those estimated for temperatures above the silicate solidus.