

Condensation of forsterite under protoplanetary disk conditions

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Meteoritic evidence indicates that dust condensation occurred in the early stage of solar system evolution. In this study, we succeeded in performing condensation experiments of forsterite under controlled protoplanetary-disk conditions, which will make significant contribution to understanding silicate formation and chemical fractionation in protoplanetary disks.

Condensation experiments were carried out in the system of Mg_2SiO_4 - H_2 - H_2O . A mixed gas of H_2 and H_2O was flowed into a continuously evacuated infrared vacuum furnace at a controlled rate to keep a pressure constant. Synthetic forsterite powder in an Ir crucible was heated as a gas source. A part of evaporated gases were condensed on a Pt mesh located at a cooler region in the chamber. The pressure and temperature conditions were close to those of protoplanetary disks. The total pressure of the system was 5.5 Pa, and the substrate temperature ranged from 1320 to 1160 K. The H_2O/H_2 ratio was set at 0.015, which was about 15 times larger than the solar ratio. The SiO/H_2 ratio was evaluated to be about 0.7-2 % of the solar ratio from the weight loss rate of the gas-source forsterite. Experimental duration ranged from 6 to 237 hours.

Sub-micron to micron-sized condensates covered with Pt substrates at 1160 and 1275 K, but no condensates were found at 1320 K. The typical size of condensates at 1160 K was less than 1 micron irrespective of experimental duration and no effective growth of each condensed grain was observed. Condensates at 1275 K for >40 hours partly had several micron-sized flat regions. EDS analyses showed that chemical compositions of condensates were consistent with the stoichiometry of forsterite, and their EBSD patterns were well fitted with the patterns from crystalline forsterite. Coincident EBSD patterns were obtained from the flat region of condensates at 1275 K, suggesting that the area was covered with a single crystal. TEM observation of condensates at 1160 K also found that the condensates were polycrystalline forsterite with a thickness of 30-150 nm, and infrared absorption spectra of condensates show clear 10-micron absorption features resembling those of crystalline forsterite. These evidence indicates that polycrystalline forsterite condensed at 1275 and 1160 K.

The mean free path of gas molecules under the present experimental conditions is less than 1 mm, and the evaporated forsteritic gas and the ambient H_2 - H_2O gas are expected to be well mixed. Supersaturation ratios (S) for experiments at 1320, 1275, and 1160 K are thus estimated to be <1.2, <10, and <1000-2000. These supersaturation ratios correspond to the supercooling of <5, <60 and <170 K, respectively.

No condensates were found at 1320 K because the degree of supersaturation was too small for nucleation of forsterite or even the vapor was not saturated with forsterite ($S < 1$). The condensates at the supercooling of <170 K (1160 K) imply that heterogeneous nucleation of new grains occurred successively on preexisting grains. On the other hand, with the supercooling of <60 K (1275 K), some grains seem to have grown up to several microns, and some seem to have newly nucleated on preexisting grains, suggesting that both nucleation and growth of each condensate occurred.

These differences would result in a structural difference in forsterite dust condensed in protoplanetary disks. Fluffy aggregates of sub-micron sized fine particle would form with a supersaturation of >1000, while aggregates of micron-sized grains would form with S of 10 that could be an analogue of amoeboid olivine aggregates in chondrites.

Keywords: forsterite, condensation, protoplanetary disk