Possibility of the Mg/Si fractionation caused by incongruent evaporation of enstatite in the primitive solar nebula

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Enstatite evaporates incongruently forming a forsterite layer as an evaporation residue and its evaporation might have played an important role for the Mg/Si fractionation in the primitive solar nebula. Incongruent evaporation experiments of enstatite were carried out in vacuum and hydrogen gas at 1300-1500C to understand its evaporation kinetics and discuss the Mg/Si fractionation in the solar nebula. Timescales of evaporation of 1 micrometer-sized enstatite grains in the solar nebula were estimated based on experimental evaporation kinetics of enstatite. The Mg/Si fractionation is expected by incongruent evaporation of enstatite in various situations in the solar nebula taking timescales of evaporation, temperature and dust enrichment relative to gas into consideration.

Incongruent evaporation experiments of enstatite were carried out in vacuum and hydrogen gas at 1300-1500C to understand its evaporation kinetics and discuss the Mg/Si fractionation in the solar nebula. Enstatite evaporates incongruently forming a forsterite layer as an evaporation residue. In vacuum, the thickness of the forsterite layer increases with time in the early stage of evaporation and then becomes constant as evaporation proceeds. In the early stage of evaporation, it is considered that the surface reaction controls evaporation of enstatite because the thickness of the forsterite layer increased almost linearly with time. On the other hand, the constant thickness of the forsterite layer is explained by diffusion-controlled evaporation. The net formation rate of the forsterite layer is given by the difference between the diffusion-controlled evaporation rate of enstatite and the evaporation rate of forsterite since residual forsterite also evaporates. Since the diffusion-controlled evaporation rate of enstatite depends on the thickness of the forsterite layer, it becomes equal to the evaporation rate of forsterite at a specific thickness, and the net formation rate of forsterite becomes zero for further evaporation (steady state). The diffusion-controlled evaporation mode appears probably when the porous forsterite layer becomes compact due to grain growth on the surface of enstatite. We obtained the diffusion-controlled evaporation rate constant of enstatite from the constant thickness of the forsterite layer.

A thinner forsterite layer was formed in hydrogen gas than in vacuum. Evaporation of enstatite in hydrogen gas is also considered to be controlled by diffusion through the forsterite layer. The thin forsterite layer formed in hydrogen gas is ascribed to the enhanced evaporation rate of forsterite in the presence of hydrogen gas.

There are three different evaporation behaviors for incongruent evaporation of enstatite depending on temperature and a dust enrichment factor relative to the solar abundance (h); complete evaporation (CE), partial evaporation with equilibration between residual forsterite and gas (PE/F), and partial evaporation with equilibration between enstatite, residual forsterite and gas (PE/EF).

In the case of PE/F, forsterite alone is left in the system in the final state, and the Mg/Si ratio in gas ranges from 1 to less than 0.2 at equilibrium depending on h. Hence, the Mg/Si fractionation would occur if solid-gas separation took place. Under the condition of PE/EF, the Mg/Si ratio in solid at equilibrium varies from 2 to 1 as h increases, while the Mg/Si ratio in gas at equilibrium is smaller than the original ratio and constant irrespective of h. Thus, the Mg/Si fractionation is expected in the case of PE/EF as well.

Timescales of evaporation of 1 micrometer-sized enstatite grains in the nebula were estimated by numerical calculations based on experimental evaporation kinetics of enstatite. They were about several hours, a day to a few months and a week to a few hundred years at 1400, 1100 and 900C, respectively.

At high temperature (1400-1200C), highly dust enrichment (h >several hundreds) would be needed for the fractionation. Settlement of dust grains to the nebular midplane might have made this situation as long as there were extra heating mechanisms. At temperatures of 1200-1000C, modest dust enrichment (several to several tens times) would be enough for the fractionation. This situation might occur in the turbulent solar nebula and turbulence would work as a heat source and for solid-gas separation. At lower temperature (<1000C), dust-depleted (h<1) conditions would be suitable for the fractionation. This condition would be made as a counterpart of the dust-enriched condition in the turbulent nebula or during dust-settlement.