

CONDENSATION KINETICS OF FORSTERITE AND METAL AND CHEMICAL FRACTIONATION IN THE PROTO SOLAR NEBULA. H. Nagahara¹ and K. Ozawa², ¹Dept. Earth Planet. Sci., The Univ. Tokyo (7-3-1 Hongo, Tokyo 113-0033, Japan and hiroko@eps.s.u-tokyo.ac.jp), ²Dept. Earth Planet. Sci., The Univ. Tokyo (ozawa@eps.s.u-tokyo.ac.jp).

Introduction: Protolplanetary accretion discs evolve in combination of physical and chemical processes, which finally resulted in diversity in planetary compositions. The evolution models for young discs have concerned density and thermal structure of steadily accretion discs (e.g. [1][2]), dynamics of discs including evaluation of α -viscosity (e.g., [3]), and material transport in 2-D models (e.g., [4]). Recent development of IR or radio observations also give us information about structure of discs, such as temperature, density and material distribution. Because the thermal structure is dependent on species, size distribution, and occurrence of solid phases in a radiation field, which in turn affects the stability of solid materials, it is crucial to investigate evolution of dusts in connection with disc physics. Contrary to development of models and astrophysical observation, origin of meteorites within the evolution of prot-solar disc have been hardly understood despite pile of mineralogical and isotopic data. CAIs and chondrules have recently been thought to be products of shock heating, which are instantaneous processes that can not be linked with long term disk evolution.

Purpose: Although chemical equilibrium is the first step guide line for the stability of condensed phases, it does not give any information about time-dependent processes. Condensation and evaporation are the two major phase changes that takes place in protoplanetary discs at low pressure, of which rate is a function of pressure, temperature, and composition of the nebular gas. The rate is shown as the Hertz-Knudsen equation, which includes a kinetic parameter for surface reactions that are determined by experiments. Condensation contains two elemental processes, nucleation and growth, and there are two types of condensation, homogeneous and heterogeneous. Homogeneous nucleation is often assumed for dust formation, through which different phases condense as independent grains, whereas heterogeneous nucleation results in formation of chemically reacted, composite, or mantled grains. The mode of nucleation thus affects the grain size and subsequent condensation, which is controlled by surface tension and the degree of supersaturation. We have investigated condensation of Mg-silicates and Fe metal, two most major constituents of the terrestrial planets, by model calculation taking the mode of condensation into consideration.

Condensation model: We have investigated condensation sequence and their grain size distribution in a cooling gas system with special interest to the critical condition for homogeneous/heterogeneous condensation of metallic iron onto Mg-silicate (forsterite). The model consists of two basic equations: (a) the nucleation and growth rate as a function of gas velocity, abundance of the gas species concerned, and condensation coefficient, and (b) net mass conservation, which represents that the concentration of gas species concerned decreases with progress of condensation. The model contains two parameters, total pressure, P_{tot} , and cooling time, τ .

The system consists of H, He, C, O, Mg, Si, and Fe with the solar abundance ratios, and we did not consider refractory elements (Al, Ca, and Ti) and other trace moderately volatile elements (P, Cr, Mn, K, and Na) in order to elucidate the role of heterogeneous condensation. Nucleation of forsterite is assumed to take place homogeneously, of which timing is defined simply by the surface tension. Metal nucleates heterogeneously at $\sigma=7$ on forsterite because forsterite condenses always prior to Fe. σ is the degree of supersaturation, which is defined as the partial pressure of species i over its equilibrium partial pressure at a certain temperature-total pressure condition. The $\sigma=7$ is the value we have experimentally obtained. The cooling time ranged $\tau=10^2$ to 10^{12} sec ($\sim 3 \times 10^5$ yrs), which corresponds to instantaneous cooling such as shock cooling and nebular scale cooling, respectively. The total pressure ranges $P_{tot}=10^{-9}$ to 10^{-2} bar. The condensation coefficient of Fe is taken to be 1, although our recent experiments suggest slightly lower value at certain conditions. Those of forsterite and enstatite are assumed to be 0.1, which has not yet to be experimentally determined, and we use rough value of condensation coefficient.

The solid phases include forsterite, enstatite, and SiO₂, all of which are assumed to be crystalline, though it is not evident. This assumption is also very simplified, and there is a possibility that amorphous SiO₂ or amorphous Mg-silicate appear instead. Because their thermochemical natures are not uniquely defined, it is generally difficult to take them into calculations. Metal is assumed to be pure Fe, and we did not consider Ni, which may result in slightly lower condensation temperature.

Results: Metallic iron condenses always heterogeneously on forsterite. The condensation sequence is divided into two cases depending on total pressure and cooling time scale; one is the case where metallic iron condenses with remaining Mg in the gas phase and another is the case where metallic iron condenses after total condensation of forsterite. The former takes place at larger cooling time (rapid cooling) and the latter at smaller cooling rate (slow cooling). The boundary moved to smaller cooling time with increasing total pressure.

Condensation sequence and phases. When gas cools rapidly, forsterite started to grow is quickly covered by metallic iron, which resulted in a grain with forsterite core and Fe mantle. Because there still remains Mg in the gas, forsterite homogeneously condenses at lower temperature, which partly reacted with gas to form enstatite at further lower temperature. Depending on the cooling condition, SiO₂ or enstatite homogeneously condenses.

Condensation sequence in slow cooling conditions is quite different. If forsterite was fully condensed when metallic iron started to condense, there remains no Mg in the gas. The forsterite is totally covered by metallic iron, which resulted in condensation of SiO₂ at lower temperature due to inhibition of enstatite formation. The micro-scale fractionation forms SiO₂, which is not a phase that appears in equilibrium.

Grain size distribution. The grain size is strongly dependent on conditions. The size of core-mantle type grains reaches an order of cm when the cooling time scale is a year and the total pressure is as high as 10(3) bar. The size becomes smaller with rapid cooling or lower pressures, and homogeneously condensed phases at lower temperatures also have small size, which goes down to an order of nanometer.

Discussion: Heterogeneous condensation greatly affects the phase and size of condensates in a cooling gas. It is worth noting that the size can be as large as mm or more, which is much larger than the dust size commonly assumed (~0.1 micron) for protoplanetary discs. Gail and his coworkers (e.g., [5]) have investigated disc evolution by combining physics and chemistry, which includes phase changes and chemical reactions. It, however, does not consider heterogeneous condensation, and their results would change if the effect is taken into consideration.

It is striking that independent grains of forsterite and metal are hardly formed in the pressure and cooling time conditions plausible for protoplanetary discs except for transient heating events. The grains with forsterite core and metallic iron mantle are the most abundant grains. The relative size of the core and mantle portions of such grains is defined by the time of

metal condensation. The relative size of Fo core is small at rapid cooling and large at slow cooling conditions, suggesting different degree of Mg fractionation against Si. If the Fo-core and Fe-mantle grains are fractionated from the system, the remaining system becomes poor in terms of the Fo and Fe-metal components, that is, Mg and Fe are fractionated against Si.

The Mg and Fe fractionation against Si has been pointed out by [6] for chondrites with various chemical groups. The fractionation among chemical groups of chondrites are well understood by fractionation of the Fo-core and Fe-mantle grains with different relative size of core to mantle. The relationship is shown in Fig. 1, where the compositions of ordinary chondrites are the results of fractionation of the core-mantle grains. The numbers in the figure show the fraction of Mg condensed when metallic iron heterogeneously condensed: H chondrites have fractionated composite grains with highest relative abundance of forsterite core and LL smallest.

Although the present work ignores the refractory component, the presence of refractory grains as the first condensates would largely affect the subsequent condensation, grain size, and composition of heterogeneously condensed grains.

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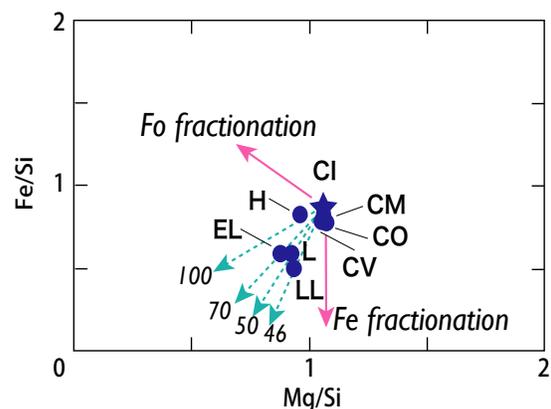


Fig. 1 Bulk composition of chondrites and the vector of fractionation of Fe and forsterite. Fractionation of core (Fo)–mantle (Fe) grains from CI produces other chondrites. The blue-green arrows are composition of fractionated core-mantle grains for H, EL, L, and LL chondrites. The numbers are the fraction of Mg condensed when Fe mantle started to condense.