

**CONDENSATION AND ITS INFERENCE ON COSMOCHEMICAL FRACTIONATION.** H. Nagahara<sup>1</sup> and K. Ozawa<sup>1</sup>, <sup>1</sup>Department of Earth and Planetary Sciences, The University of Tokyo (hiroko@eps.s.u-tokyo.ac.jp).

**Introduction:** It has been well known that chondrites and the inner planets show a fractionation trend in terms of major elements including refractory, moderately volatile and volatile elements. Depletion of moderately volatile (Mg and Si) and volatile elements, specifically depletion of Si compared to Mg, decoupling of Fe from Mg and Si, close behavior of Si and volatiles have been pointed out so far. They were explained by mixing of high- and low-temperature components [1,2], mineral fractionation during condensation [3], elemental fractionation by incomplete condensation [4,5], or radial transport of fractionated gas [6]. All of them suggest that the proto-solar nebula had once totally evaporated and that fractionation took place between condensates and remaining gas during subsequent cooling.

Those studies, however, were just in the composition space, and did not consider physical processes of condensation, dust coagulation, and motion of gas and dusts in the disc. The fractionation, thus, should be examined quantitatively as to evaluate whether gas/dust fractionation could take place in an evolving solar nebula with reference to dust condensation and growth, dust and gas transport, and cooling of the nebula. It should further explain the difference in processes responsible for the two fractionation trends, the trend that makes ordinary and enstatite chondrites and that for carbonaceous chondrites (Figs. 1 & 2).

**Heterogeneous condensation:** Grains are assumed to condense homogeneously in previous kinetic condensation theory [7]; that is, individual phases condense independently from other phases. The size is controlled by the surface tension of the phase and cooling time scale of the gas. We have, however, previously shown that the mode of nucleation, whether homogeneous or heterogeneous, is crucial for subsequent dust evolution [8]: for example, SiO<sub>2</sub>, which does not appear in the equilibrium theory, appears if Fe metal heterogeneously condenses onto previously condensed forsterite to prevent the reaction between forsterite and the remaining gas. The size distribution is also quite different if heterogeneous condensation takes place; the size of a heterogeneously condensed grain is much larger than that of homogeneously condensed grain, because it does not need nucleation delay due to the presence of previously condensed phase(s). We, therefore, evaluate the mode of condensation on the basis of experimental results by our group, though further experiments are needed.

**Model:** We have developed a kinetic condensation model, which is an extension of our previous model [8]. It calculates condensation path of minerals in a cooling gas, the grain size distribution of phases, and the change of bulk compositions of condensates and residual gas. The model consists of two basic equations: nucleation and growth rate as a function of gas velocity and net mass conservation. The former takes the condensation coefficient (condensation probability of colliding gas molecules) into consideration. The critical condition for heterogeneous condensation and condensation coefficients are based on experimental results by our group. The latter equation, mass conservation, describes the change of gas composition due to condensation and separation of condensates. The model contains three free parameters, total pressure,  $P_{tot}$ , cooling time,  $\tau$  of gas, and critical size of grains that are separated from the remaining gas. The model further includes the effect of separation of condensed phase(s) from remaining gas, which is easily expected for non-turbulent disc where large dust grains settle to the midplane more rapidly than smaller grains. It can cause chemical fractionation in the disc.

The system consists of H, He, C, O, Mg, Al, Si, Ca and Fe with the solar abundance ratios. We did not consider other trace moderately volatile elements (P, Cr, Mn, K, and Na) in order to elucidate the role of heterogeneous condensation. Nucleation of corundum is assumed to take place homogeneously, of which timing is defined by the relationship between surface tension of corundum and cooling time scale of the gas. Forsterite condensation is either homogeneous or heterogeneous on corundum (and hibonite) depending on the degree of separation of corundum. Metal nucleates almost always heterogeneously, because corundum and forsterite condense before metal. 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 solid phases are assumed to be crystalline, though it is not evident, and there is a possibility that amorphous SiO<sub>2</sub> or amorphous Mg-silicate appear instead. Because their thermochemical properties are not uniquely defined, it is 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:** Corundum condenses homogeneously at first, and the following sequence depends on the critical size of separation of corundum. When the critical size for separation is small, subsequent condensation proceeds heterogeneously on the corundum. Due to small number density of corundum, the final grain size becomes large due to successive condensation of forsterite and metal, which prevents the reaction between forsterite and remaining gas. The remaining gas becomes enriched in Si and other volatiles. This means co-variation of Mg-Al-Fe, whereas Si alone behaves independently from those elements.

If corundum, the first condensate, (and hibonite) is separated efficiently from the gas, subsequent condensation sequence is the same as that in the system without Al (and Ca). The behavior of Al is independent of Mg, Si, and Fe, and that of Mg/Si/Fe varies depending on the two parameters, cooling time scale and critical size for separation.

The smaller Mg/Si ratios than the CI ratios are explained only by condensation of residual gas after separation of forsterite.

**Discussion:** The different condensation sequence due to the difference in the degree of separation of corundum in the early stage well explains the chemical fractionation trends for carbonaceous chondrites and for ordinary and enstatite chondrites. When corundum is effectively separated, forsterite condenses homogeneously and then Fe heterogeneously condenses on forsterite. The size of corundum varies from 1mm for the cooling time of  $10^4$  yr to  $\sim 10$  nm for the cooling time of chondrule formation. The chemical fractionation trend for carbonaceous chondrites is understood by effective separation of corundum in the early stage of condensation, which took place in slowly cooling gas, of which time scale is thousands years or longer. The separated phase should have been settled down to the midplane of the disc, and later condensates settled successively. If accretion of later condensates was not enough due to smaller grain size of the condensates or rapid accretion to a planetesimal, the Al/Si ratio becomes higher, which is the case for CV and CM and CO with the smaller efficiency.

The trend for ordinary and enstatite chondrites is explained by retention of small corundum grains in the gas and heterogeneous condensation of forsterite and Fe onto corundum to form composite grains. The trend observed in Fig. 1 is due to the enrichment of Si, suggesting that they are condensates from gas from which larger composite grains that contains forsterite were separated. The constant Mg/Al ratio is due to the coexistence of the elements in the same grains.

The higher Mg/Si and Al/Si ratios of the Earth relative to chondrites and the fractionation trends discuss-

ed above suggest the following scenario on the chemical evolution of the early solar nebula. The nebula was totally evaporated in the early stage even in the a few A.U. The gas cooled slowly in the early stage to condense refractory minerals, which were effectively accreted to the midplane, and a fraction of later condensates accreted together to form precursor of carbonaceous chondrites. The composite grains of corundum, forsterite and Fe with large sizes moved inward rapidly, which later formed the Earth and probably Venus with Mg/Si $\sim$ 1.3. The composite grains formed in fairly rapidly cooled gas in the later stage accreted to form protoplanets of ordinary and enstatite chondrites.

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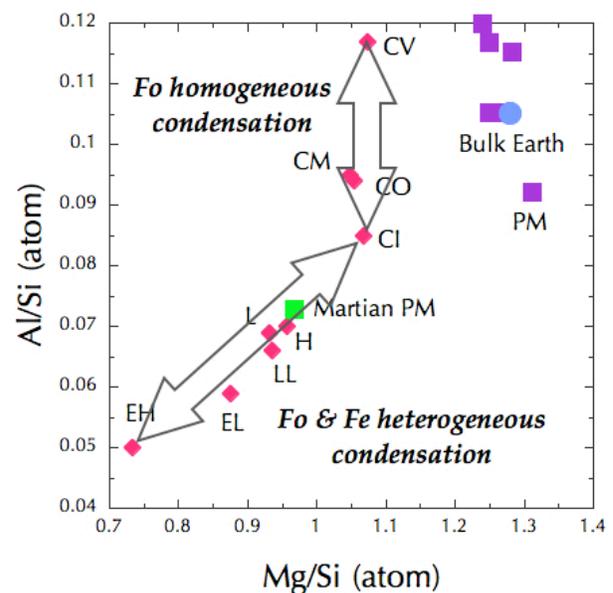


Fig. 1 "Cosmochemical fractionation" of the major elements Al, Mg, and Si, and the two trends due to difference in the separation of Al<sub>2</sub>O<sub>3</sub> from the residual gas in the early stage of condensation, which is responsible for the difference in the trend between ordinary (and enstatite) chondrites and carbonaceous chondrites. Data source: Bulk Earth [9], PM (Earth's primitive mantle) [10-14], and Martian PM [15, 16]. Meteorite data are averages.