

Dynamic Evolution of Major Element Chemistry in Protoplanetary Disks.

Y. Miyazaki^{1,2} and J. Korenaga¹, ¹Department of Earth and Planetary Sciences, Yale University, ²Now at Division of Geological and Planetary Sciences, California Institute of Technology (ymiya@caltech.edu).

Introduction: Chondrites are considered to be a promising candidate for the building blocks of Earth, and identifying the group of chondrites that best represents Earth is a key to resolving the bulk chemistry, volatile inventory, and redox state of bulk silicate Earth. No group of chondrites, however, matches the mantle in terms of both chemical and isotopic compositions [1-3]. Their major element compositions, in particular, are puzzling, exhibiting depletion in Al, Ca, and Mg against the perspective of the volatility trend. The nebular gas dissipates as the protoplanetary disk cools down, so depletion is expected for volatile rather than refractory elements [4-5].

The compositions of chondrites have been explained by different proportions of their constituents: CAI, chondrule, metallic iron, and matrix, but the depletion in Al, Ca, and Mg observed in ordinary and enstatite chondrites cannot be explained by simply losing certain components. The degree of Al- and Ca-depletion in ordinary and enstatite chondrites is larger than 20%, whereas the relative amount of Al that is present in CAIs is less than 10% for carbonaceous chondrites [6], so losing all of CAIs accounts for less than half of observed depletion.

A possible explanation is that, whereas the transport of non-refractory minerals is prohibited by evaporation, Al-, Ca-, and Mg-rich minerals are all preferentially delivered towards the Sun, and chondrites originated from a reservoir depleted in refractory elements [7]. It is unclear, however, that the preferential loss of forsterite (Mg_2SiO_4), which may create Mg-depletion, could actually take place in the protoplanetary disk. The evaporation temperature of enstatite ($MgSiO_3$) is only ~ 100 K lower than that of forsterite, so it is unclear whether forsterite can decouple from enstatite.

To this end, we create an astrophysical model of protoplanetary disks that incorporates condensation theory in a self-consistent manner. Our model tracks actual gaseous and mineral species, so the interplay between transport, condensation and evaporation of minerals can be modeled. For instance, when enstatite drifts inward, it first dissociates to yield forsterite and SiO before its complete evaporation, and such behavior cannot be described in a model that groups several minerals into a single component as “silicates.” Tracking actual species is a key to investigate

fractionation among major elements, in particular, that between Mg and Si.

Methods: We build a 1-D thermochemical evolution model of the protoplanetary disk, which solves for the radial motions of chemical species using the advection-diffusion equation [8,9]:

$$\frac{\partial \Sigma_i}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(-rv_i \Sigma_i + rv \Sigma \frac{\partial \Sigma_i}{\partial r} \right) + S_i,$$

where Σ_i denotes the surface density of species i , r is the distance from the Sun, v_i is the advection velocity, v is viscosity, and Σ is the total surface density. Evaporation and condensation of minerals are

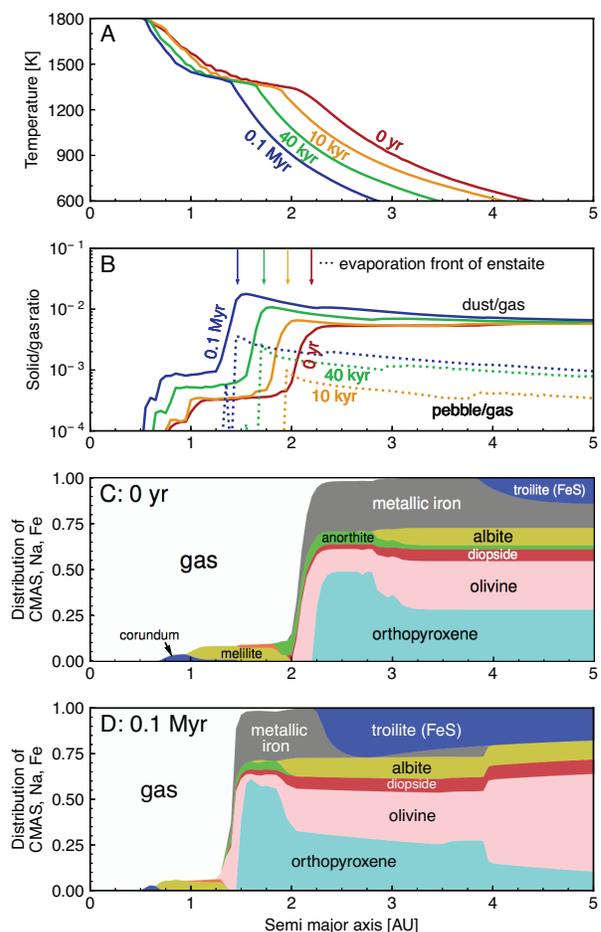


Figure 1. Snapshots of disk evolution for (A) temperature and (B) the solid/gas ratio. (C, D) Predicted mineral assemblages of the system at (C) $t=0$ yr and (D) $t=0.1$ Myr. The relative molar amount of solid-composing elements, Na, Mg, Al, Si, Ca, and Fe, in the solid phase is plotted as a function of heliocentric distance.

implemented through the source term S_i , which is calculated using Gibbs energy minimization.

Results: The physical evolution of the disk is similar to previous models [5, 8], where temperature gradually decreases, and solid is enriched in the inner region as pebbles are transported inward by radial drifting (**Figure 1**). Predicted mineral assemblages, however, indicate the new aspects of the protoplanetary disk chemistry, where, in regions where minerals evaporate, constituent elements are enriched by the transport of pebbles, altering mineral compositions. Fractionation between Mg and Si is driven by the loss of forsterite in the region where enstatite evaporates (the evaporation front of enstatite). The ratio between enstatite (orthopyroxene) and forsterite (olivine) decreases from ~ 0.17 to ~ 0.05 after 0.1 Myr of evolution (Figure 1C, D). The value of 0.05 is consistent with EH chondrites [10].

The region around the evaporation front also has the highest dust concentration inside the snow line due to the inward flux of pebbles from the outer region. The pebble/gas ratio is closest to the threshold of the streaming instability [11] around the evaporation front of enstatite, and thus there is a high probability that the instability is triggered therein.

Discussions: To explain the depletion of refractory elements observed in ordinary and enstatite chondrites, some mechanism to create nebula-wide fractionation must have operated. Considering that the protoplanetary disk was sufficiently hot to evaporate silicates only in the first million year of evolution, such a mechanism has to create the depletion quickly, and the building blocks of those chondrites must also be formed from the depleted region. The streaming instability occurring around the evaporation front of enstatite could be a way to satisfying both constraints.

Also, in the region around the evaporation front of enstatite, the Mg/Si ratio changes significantly within a narrow region (**Figure 2**), where enrichment in Mg (Mg/Si ~ 1.02 – 1.05) is observed just inside the region where Mg is depleted. Considering that the bulk silicate Earth shows an enrichment in Mg, this suggests that planetesimals formed inside and outside the evaporation front of enstatite, respectively, may have served as the sources for Earth and enstatite chondrites. Because the source regions for these two bodies are nearby, they are expected to have similar isotopic compositions, and this would explain why Earth and enstatite chondrites share isotopic compositions despite the difference in their bulk compositions.

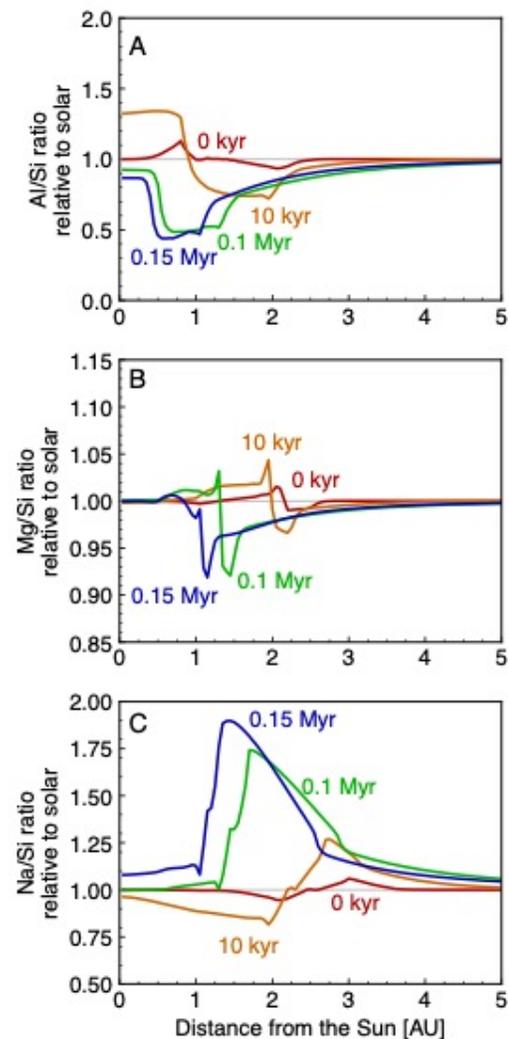


Figure 2. The evolution of the relative abundance profiles of (A) Al/Si, (B) Mg/Si, and (C) Na/Si normalized by the solar composition.

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