

**CHEMICAL CONSEQUENCE OF DUST SETTLING IN PROTOPLANETARY DISK.** Y. Miyazaki<sup>1</sup> and J. Korenaga<sup>1</sup>, <sup>1</sup>Department of Geology and Geophysics, Yale University, New Haven, Connecticut, USA (yoshinori.miyazaki@yale.edu).

**Introduction:** Dust particles in protoplanetary disk settle to the mid-plane under the influence of stellar gravity and centrifugal force, and they grow in size as they settle. Particles larger than cm-size tend to decouple themselves from the gas and drift inward radially to their central stars, but the drifting terminates once they grow into km-size [1]. This causes the redistribution of elements [2], suggesting that the evolution of grain-size is essential when discussing the chemical structure of the disk. The gravitational instability is considered to be one of the prominent processes in which micron-size particles develop into km-size planetesimals [3]. Dust settling causes mass concentration near the mid-plane, which could then satisfy the density criteria for gravitational instability. Therefore, the settling process and time scale of their process affect the subsequent disk evolution and consequently have an impact on element distribution within the disk.

The physics of dust settling has been studied both from theoretical and observational perspectives. The spectrum of protoplanetary disks around T-Tauri stars is sensitive to grain size. Recent models have incorporated the effects of coagulating and shattering of grains to explain the spectrum observations [4]. Effects of chemical condensation and evaporation have not been considered, but it is likely that those processes also play an important role in the early stage of planet formation.

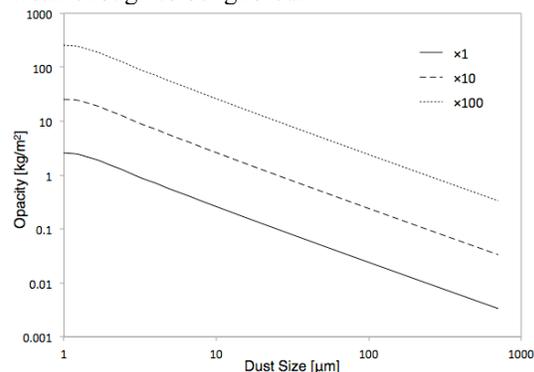
In the dust settling process, the dust is transported to near the mid-plane, raising the dust/gas ratio. It will be necessary to consider enhancement of dust/gas ratio to explain the high iron content in the silicates [5-7]. Condensation sequence of solar compositions shows that iron is not incorporated into silicate phase until 550K [8], but this is too low for the diffusion of iron into solid phases. Dust settling changes chemical dust properties as well as its amount. This process influences the density and temperature distribution, and then influences the dust compositions and proportion again. The purpose of this study is to look at the dust-settling process from physical and chemical perspectives simultaneously, and quantitatively investigate the effects of condensation and evaporation on dust settling.

**The Model:** The model calculates 1-D dust settling, while computing average chemical compositions of dust in each grid cell through the Gibbs free energy minimization. The forces applied to dust particles are gravity from the central star and gas drag. The particles reach the termination velocity within a few hours and

settle with that velocity. Grain fragmentation and sticking are not considered for simplicity. Conventional calculations used the fixed dust amount in the system, but our model determines the dust properties based on chemistry. Dust amount in each grid cell is obtained through equilibrium calculations. Each grid cell is assigned a characteristic grain size. When the dust first condenses in each cell, initial grain size is assumed to span from 0.1 $\mu\text{m}$  to 30 $\mu\text{m}$ , which is estimated from mean free path and collision frequency. Its growth occurs through additional condensation on existing grains, while conserving the number of dust particles in their grid cell.

Equilibrium calculations are made by minimizing Gibbs free energy, using the non-linear conjugate gradient method. Only the major elements (H, O, Mg, Al, Si, Ca, Fe) are included in equilibrium calculations for simplicity. Mineral species considered are corundum, melilite, spinel, olivine, and pyroxene. The dust amount in each grid is determined as the total mass of corundum and silicates.

The vertical density distribution is obtained by assuming hydrostatic equilibrium. The temperature distribution is acquired by assuming a radiation transfer. The Rosseland mean opacity used in the transfer equation is calculated through Mie-scattering computer code [9] using refractive index data of silicate by Draine [10]. Figure 1 shows the Rosseland mean opacity with different grain sizes and dust amounts. Temperature dependence of Rosseland mean opacity is weak enough to be ignored.



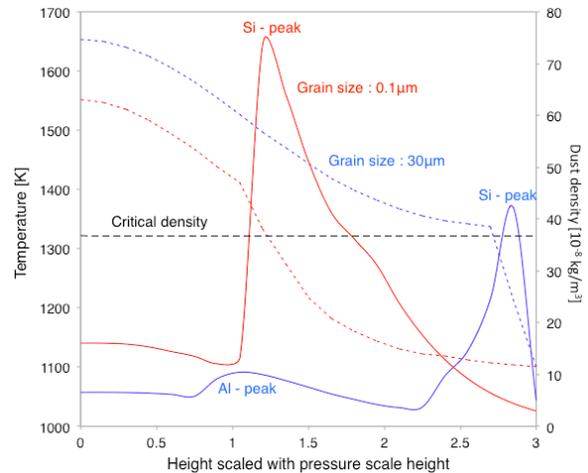
**Figure 1:** The Rosseland mean opacity of silicates as a function of dust particle radius. Cases for dust amount in solar composition (solid line), 10 times enhancement of the dust/gas ratio (dashed line), and 100 times enhancement (dotted line) are shown.

**Model Results:** The initial condition of the system is assumed to have a homogeneous solar composition and to be hot enough for no dust to exist in the beginning. Dust starts to coagulate in the upper region of the disk, and it moves toward the mid-plane. Settling of micron-size particles is slow, but it increases the dust/gas ratio of the lower grid cell. Enhancement of the ratio raises the condensation temperature of each mineral and makes it easier for the dust to emerge. Condensed dust, however, would re-evaporate as they move into a hotter region and is prevented from further settling. This forms a “condensation front”, which is the region that certain elements are concentrated above condensation temperature. Figure 2 shows the vertical distributions of temperature and dust density with upper and lower limits of initial condensing grain size. Effective temperatures for both distributions are identical, but mid-plane temperatures deviate due to the difference in opacity. Temperature rises significantly at silicate condensation front. Silicates are stagnated above the front and form a large amount of dust, resulting in large opacity value. Since the dust density increases above the condensation front, it has a potential to exceed the critical density for gravitational instability and form a km-size planetesimals.

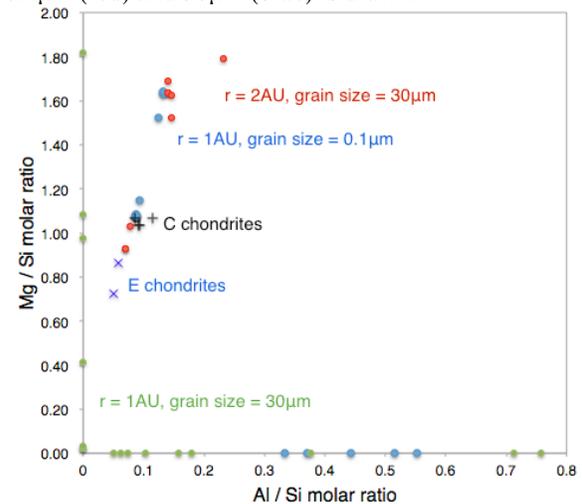
Time difference exists for the alumina dust and the silicate dust to reach the mid-plane. Therefore, Al/Si and Mg/Si molar ratios differ spatially and temporarily. Figure 3 plots the value of Al/Si and Mg/Si ratios at various heights with different parameters. Some parameters are able to explain the Al/Si and Mg/Si ratios of chondrites.

**Discussion:** Detailed calculations of chemical condensation have been intensively made in the field of cosmochemistry [11], but their results have not been incorporated into astrophysical models. The complexity of physical and chemical processes taking place in the protoplanetary disk has prevented the model formulation. A pioneering work has been made to reproduce moderately volatile elements depletion (MOVE) in carbonaceous chondrites. That shows that MOVE is a result of incomplete condensation, which means that constant removal of gas from the nebula occurred. It has been suggested, however, that incorporation of radial drift changes the model result significantly [2].

Our model assumes that a hot homogenous nebula was achieved at some point in the history. If incomplete condensation had occurred, chondrites should have had Al/Si ratio 1.5 times larger than solar abundance. Our model shows that Al/Si and Mg/Si ratios of chondrites are generated as a result of condensation induced by dust settling. Iron content in the silicate phase could also be calculated, and be compared with CAI observations as a future work.



**Figure 2:** The vertical distribution of temperatures (dashed - left axis) and dust density (solid -right axis) with the critical density for gravitational instability (black dashed). Initial condensation grain size of  $0.1\mu\text{m}$  (red) and  $30\mu\text{m}$  (blue) is drawn.



**Figure 3:** Molar ratios of Al/Si and Mg/Si. Circles show the model calculation at 1AU with  $0.1\mu\text{m}$  (blue), at 1AU with  $30\mu\text{m}$  (green), and at 2AU with  $30\mu\text{m}$  (red). Carbonaceous chondrites (black cross) and enstatite chondrites (blue cross) are also plotted.

**References:** [1] Weidenschilling S. J. (1980) *Icarus*, 44, 172-189. [2] Ciesla F. J. (2008) *Meteoritics & Planet. Sci.*, 43, 639-655. [3] Youdin A. N. and Shu F. H. (2002) *ApJ*, 580, 494-505. [4] Dullemond C. P. and Dominik C. (2005) *A&A*, 434, 971-986. [5] Wood J. A. and Hashimoto A. (1993) *GCA*, 57, 2377-2388. [6] Ebel D. S. and Grossman L. (2000) *GCA*, 64, 339-366. [7] Yoneda S. and Grossman L. (1995) *GCA*, 59, 3413-3444. [8] Grossman L. (1972) *GCA*, 36, 597-619. [9] Matzler C. (2002), *Research Report*. [10] Draine B. T. (1985) *ApJ Supplement Series*, 57, 587-594. [11] Cassen P. (1996) *Meteoritics & Planet. Sci.*, 31, 793-806.