Dust Condensation in Evolving Disks and the Compositions of Chondrites, Planetesimals, and Planets. Min Li[1], Shichun Huang[2], Michail I. Petaev[3,4], Zhaohuan Zhu[1], and Jason H. Steffen[1], [1]Department of Physics and Astronomy, University of Nevada, Las Vegas, 89154, USA, min.li@unlv.edu, jason.steffen@unlv.edu [2]Department of Geoscience, UNLV, 89154, USA, [3]Department of Earth & Planetary Sciences, Harvard University, 20 Oxford St., Cambridge 02138, USA [4]Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge 02138, USA

Introduction: All terrestrial planets [1-3] and many carbonaceous chondrites (CM, CO, and CV) [4] are depleted in volatile and enriched in refractory elements relative to the composition of the Sun (as represented by CI the chondrites [5]). The degree of elemental depletion is correlated with their volatility [6].

The volatile depletion in rocky planets is commonly attributed to a partial condensation of dust in the solar nebula accompanied by a loss of gas [7]. Since planetesimals and planets form in protoplanetary disks, their compositions should be a function of both the evolution of the gaseous disk and the condensation of the elements in it. Here, we use a combined physical and chemical model to study the evolution of a solar disk, and to test under which conditions the volatile depletion patterns in chondrites can be reproduced.

Method: We assume that the elements are partitioned among three phases: one gaseous and two condensed — advected dust and decoupled dust (See Figure 1). At given temperature and pressure at the disk midplane, the condensation of elements is modeled either explicitly by chemical equilibrium calculation (Models M2), or based on 50% condensation temperatures (T50) when a given element is equi-partitioned between the condensed and gasesous phases (Models M1)). The dust decouples from the gas on a timescale proportional to the local orbital period. As the disk evolves, the portion of the dust that has not decoupled from the gas, the advected dust, move with the gas.

Disk evolution model. We adopt the disk model used by Cassen [7] to calculate the evolution of the disk. The surface density is

$$\Sigma = \Sigma_0(t)\exp\{-[r/r_0(t)]^2\},$$

where $\Sigma_0(t)$ is the surface density near the central star and $r_0(t)$ is the characteristic radius. In the evolving disk, we calculate the midplane temperature $T(r,t)$ and pressure $P(r,t)$ at each radius r and time t.

Dust Condensation. Dust Condensation is calculated assuming full chemical equilibrium with the GRAINS code [8] for 33 elements (See Table 1) in the evolving disk. As a result, we get the chemical composition of the decoupled dust (=planetesimals/planets) at each radius in the disk

To compare with the results of Cassen [7], we also calculated the condensation of the elements based on T50 of all elements at 10−4 bar. The T50 for the gas of solar composition were calculated at different pressures using the GRAINS code

Table 1. Elements used in our model

H	He	C	N	O	Na	Mg	Al	Si	P	S
Cl	K	Ca	Ti	Cr	Mn	Fe	Co	Ni	Cu	Ga
Ge	Mo	Ru	Pd	Hf	W	Re	Os	Ir	Pt	Au

T_{50} at different pressure: Figure 1 (right) shows the effect of pressure on the T50s in the range of 10−12 to 1 bar. While all T50 increase with increasing pressure, there are also some changes in order of element condensation.

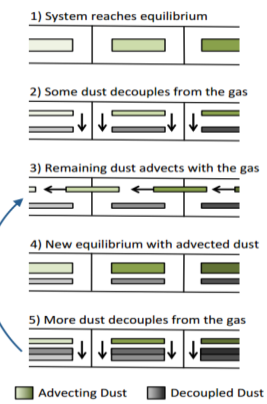
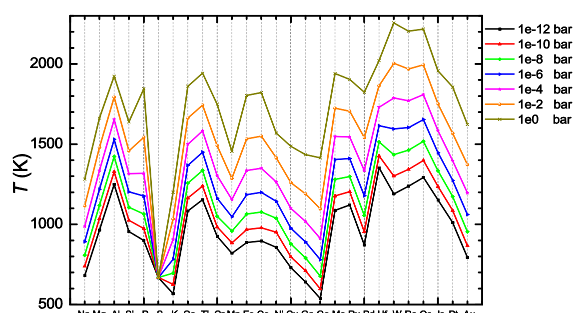


Figure 1. Left - a flow chart of our model; calculations are done at each time step. Below - T_{50} of the gas of solar composition as a function of pressure



Results: The evolution of the disk was modeled using different disk evolution and dust decoupling timescales and dust decoupling scenarios (Table 2).

Chemical equilibrium (M2) models. Figure 2 shows how elemental abundances of the decoupled dust evolve with time. As time goes on, the condensation region expands both inward (due to cooling of the

Table 2. Different models and disk evolution and dust decoupling timescales

Time-scales	Models with T_{50} (M1)		Time-dependent chemical equilibrium model (M2)			
	Typical values (M1G1)	Group 3 (M1G3)	Typical value (M2G1)	Group 2 (M2G2)	Group 3 (M2G3)	Group 2 (M2G4)
$t_{dec/yr}$	1.5e4	1.5e3	1.5e4	1.5e5	1.5e3	1.5e6
$t_{e/yr}$	2.625e4	2.625e4	2.625e4	2.625e4	2.625e4	2.625e6

inner region) and outward (due to the gas surface density increase caused by viscosity and the outward flow of disk material). As a result, the relative elemental abundances of decoupled dust change with time.

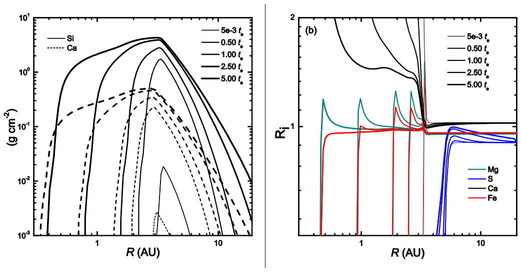


Figure 2. Left: Evolution of Si and Ca in the decoupled dust for the typical model (M2G1). Si and Ca are shown by solid and dashed lines, respectively. Over time the inner condensation front moves inward as the temperature decreases and the outer front moves outward as the surface density rises. Right: Ca, Mg, Fe, and S relative abundances as a function of radius and time.

Relative abundances. Relative abundances for both M2 and M1 models at time $t = 5t_e$ are shown in Figures 3 and 4.

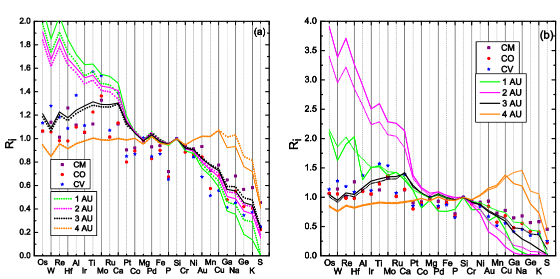


Figure 3. Equilibrium vs 50% condensation models: Comparison of relative abundance calculated at the end of the simulation. Left: The chemical equilibrium model (M2G1, solid lines) and the fixed T_{50} model (M1G1, short dotted lines) for the elements are shown. Right: The chemical equilibrium model (M2G3, solid lines) and the fixed T_{50} model (M1G3, short dotted lines) for the elements are shown.

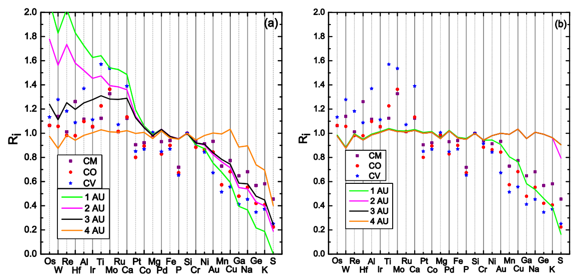


Figure 4. Relative abundance at the end of the simulation for model M2G2 (left) and M2G4 (right). The results for model M2G2 is generally the same as that for model M2G1.

Conclusions: (i) The condensation front of each element expands inward and outward from its initial condensation region. (ii) For the typical case here, the relative elemental abundances in the decoupled dust decrease with time and distance for refractory elements and increase for volatile elementswithin ~ 3 AU. The resulting decoupled materials are enriched in refractory elements and depleted in volatile elements relative to the starting (solar) composition. The dust accumulated at 3 AU most closely matches the observed chemical compositions of CM, CO, and CV chondrites. (iii) The relative elemental abundances calculated for full chemical equilibrium (M2) models are slightly higher for refractory elements and lower for volatile elements within 3 AU compared to the fixed T50 (M1) models. (iv) The relative elemental abundances do not change significantly when the decoupling timescale is longer than or similar to the disk evolution timescale. (v) If the decoupling time is short, there will be peaks in the abundance distribution as a function of the condensation temperature. (vi) When the initial temperature in the disk is high, the decoupled dust is enriched in refractory and depleted in volatile elements relative to the starting composition. When the initial temperature is low, the abundances of refractory elements in the decoupled dust are close to solar values. Thus, the relative elemental abundance is affected by the temperature history of the disk.

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