RADIAL MIXING IN THE PROTO-SOLAR DISK AND CHEMICAL COMPOSITION OF METEORITES.

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Introduction: The cometary samples collected by the Stardust mission showed us that fragments of CAIs formed at the inner edge of the protosolar disk and fragments of chondrules which probably were formed at the asteroid belt, though not so clear, were transported outward and incorporated into an icy body [1, 2]. Also found are amorphous silicate-bearing GEMS and presolar grains [3, 4], which are clear evidence for survival of raw materials from thermal processing and which had not transported to the inner warm region of the proto-solar disk.

Despite most, but not all, physical models and even astrophysical observations that temperature of proto-planetary disks are low, cosmochemical studies on meteorites and IDPs have revealed that the protosolar disks has once heated to temperatures high enough to mostly evaporate to gas and memories of the high temperature stage had preserved in planetesimals. The clearest evidence is the volatility controlled bulk chemical composition of chondrites, in particular, carbonaceous chondrites, which never can be formed by a fractionation process other than evaporation/ condensation. Another important evidence is the isotopic homogeneity of almost all elements except for oxygen and some other light elements.

Recent chronological work gives another important constraint on the dynamics of the proto-solar disk that at least some differentiated meteorites were formed and melted to separate the core simultaneous with or earlier than chondrites, which are date to be ~2 m. y. after CAIs and are earlier than some chondrules [5-7]. Possible heat source for melting and differentiation of small bodies have been thought to be the presence of ^{26}Al, of which effect is larger if the formation age is earlier and if the abundance is larger.

Above observations suggest that planetesimals rich in a refractory component and poor in volatiles such as the angrite parent body were formed at an early stage, whereas, chondrites that were not differentiated were formed at a relatively later stage.

Purpose: We investigate physico-chemical evolution of the proto-solar disk at the early stage by developing a new model that combines physics and chemistry with special interest to temporal and spatial evolution of the disk. Then, we discuss how the composition of planetesimals varies depending on the time and space for their formation including refractory or volatile rich ones.

Model and conditions: The present work evaluates the temporal and spatial evolution of mixing of materials in the proto-solar disk, which is based on the model by Ciesla [8, 9]. The basic of the model is a radial advection-diffusion equation, which includes drift and dispersion by turbulence with stochastic diffusion term calculated by the Monte Carlo method and which shows the diffusivity by the viscosity of the disk. The difference from conventional disk models is that the present method stands on the Lagrangean differentiation, and it is able to trace the movement of individual particles. The validity of the model compared to the conventional Euler differentiation models has been fully confirmed by Ciesla [8, 9].

The surface density of the disk is inversely correlated with the distance and time; temperature is in the inverse square relation to the distance, where T>1300K at R<2.5AU and t=0, 650K at 2AU and 10^5 yrs and 350K at 2AU and 10^6 yrs; the initial mass of the disk is 0.1 solar mass without additional input; grain size of particles is 1 micron all through the calculations, that is, the role of coagulation is not included. The small particle size means coupling of dust particles with gas. We divide the disk from 0.5 to 100AU into 16 bins and put 10^5 particles in each bin. The mass of the disk at a certain distance from the proto-sun was obtained by multiplying the surface density to the annular area. The calculation was carried out for 10^6 years.

We (1) trace the *R-T-P* (*R*: heliocentric distance from the porto-Sun, *T*: temperature, *P*: pressure) trajectory of individual grains, (2) count the number of grains remained in the disk as a function of *R* and *t* (time), and (3) count the number of grains that experienced high temperature (1000K and 1400K), which were mostly from the inner region and which was transported outward by diffusion and convection with lesser amount of grains originating from the outer region and going back and forth.

Results and discussions: The mass of the disk decreases rapidly with time in the present model as Ciesla [8] had already pointed out, because no later accretion is taken into the model, which becomes almost half of the initial disk mass in 10^4 yrs, ~0.2 in 10^5 yrs, and 0.05 in 10^6 yrs.

The details of radial mixing are shown in Fig. 1, where the colors represent the initial positions in the disk: warm colors are initially in the inner (<5AU) regions and cool colors in the outer regions. A considerable amount of materials in the inner regions are transported outward at the early stage (t < 10^5 yrs), which is because the surface density is much larger in the inner region at the early stage of the disk evolution. Although the outward flux is large at the early stage, there comes a larger amount of materials from the outer region even within $1\text{x}10^5$ yrs. The mixing ratio of materials from the inner regions to outer regions is almost unity within several AU all through the disk evolution, suggesting that thermally processed materials and unprocessed materials were mixed in the inner region of the disk. It is important that the relative abundance of materials from outer regions becomes larger with time, which implies that planetesimals formed within several AU at the early stage of the disk evolution consists partly of materials initially located at the inner regions and partly from outer regions, but those formed at the later stage contain more abundant raw materials transported from the outer regions.

In order to evaluate the relationship between chemical composition of planetesimals and disk evolution, the fraction of particles that experienced high temperature was counted. Figure 2 shows the fraction of grains that experienced above 1400K and 700K in the time and heliocentric distance space. Particles experienced T>1400K are highly refractory being rich in Al and other refractory elements, that is, rich in ^{26}Al at the early stage. Combining Figs. 1 and 2, we can roughly estimate the conditions for CV chondrites, which is enriched in refractory elements by ~1.4 times than CI. The conditions that the fraction of T>1400K materials occupies ~40% of total remaining materials are satisfied no later than ~10^5 yrs.

The temperature of 700K roughly corresponds to the condensation/evaporation temperature of sulfur in troilite. Sulfur is crucial when we consider its depletion in chondrites and terrestrial planets, which is 0.2-0.4 times of the CI abundance ratio in carbonaceous chondrites other than CI and ordinary chondrites. Assuming that planetesimals were formed from materials that remained in the disk and that the materials originated in the outer regions which do not experience high temperatures have compositions with the solar abundance elemental ratios, highly sulfur depleted chondrites should have been formed at relatively inner region of the disk and not late stage.

Conclusions: The present work shows how radial mixing in the proto-solar disk proceed as a function of distance from the proto-sun and time. The mixing ratio of materials from the inner and outer regions is almost unity at the early stage but the fraction of materials from the outer regions increases with time. Combining the information about the maximum temperature that the particles experienced, we can constrain that early differentiated planetesimals such as the parent body of angrites and planetesimals with refractory-rich compositions such as CV chondrites were formed at the inner region of the disk in ~10^5 yrs. On the other hand, planetesimals for other carbonaceous chondrites or ordinary chondrites that are depleted in sulfur were formed later, possibly at ~10^6 yrs. More quantitative discussion to evaluate composition of meteorites and the abundance of ^{26}Al needs introduction of equilibrium calculation into the model.

References: [1] Brownlee D. et al. (2006) *Science, 314,* 1711. [2] Zolensky M. et al. (2006) *Science, 314,* 1735. [3] Keller L. P. and Messenger S. (2005) *ASPS Series* 341, 657. [4] Floss C. et al. (2002) *GCA 75,* 5336. [5] Connelly J. N. et al. (2012) *Science* 338, 2107. [6] Kruijer T. et al. (2012) *GCA* 99, 287. [7] Klein T. et al. (2012) *GCA* 84, 186. [8] Ciesla F. (2010) *Icarus* 208, 455. [9] Ciesla F. (2011) *ApJ* 740, 1.

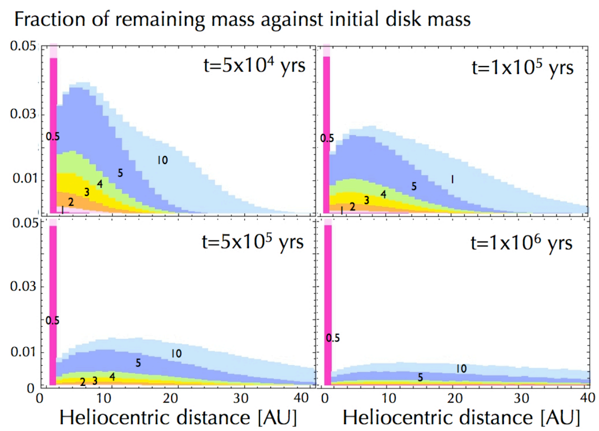

Fig. 1 Evolution of radial mixing in the proto-solar disk. The materials are colored by their initial locations, which are shown in the figure by the numbers [AU]. The vertical is the fraction against the initial disk mass.

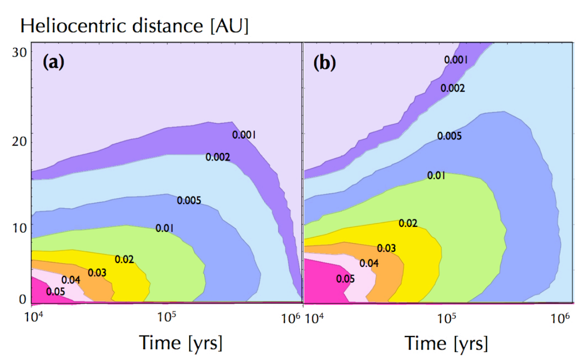

Fig. 2 Spatial and temporal variation of materials experienced high temperature: (a) T>1400K and (b) T>700K. The numbers within the figures represent fraction of those particles against the initial disk mass.