CHEMICAL EVOLUTION OF THE EARLY STAGE OF A PROTOPLANETARY DISK AND ITS INFERENCE ON THE CHEMICAL COMPOSITION OF CHONDRITES. H. Nagahara\textsuperscript{1}, M. Nakata\textsuperscript{1}, and K. Ozawa\textsuperscript{1}, \textsuperscript{1}Dept. Earth Planetary Sci, The Univ. Tokyo (hiroko@eps.s.u-tokyo.ac.jp, ozawa@eps.s.u-tokyo.ac.jp).

**Introduction:** Evolution of protoplanetary disks has been studied extensively for three decades, which showed that planetesimal formation is the first step for the following planet formation. Finding of various exoplanetary systems and fragments of chondritic materials in comets have revealed highly dynamic pictures of protoplanetary disk evolution.

Cassen [1,2] were the first who tried to combine physics and chemistry of disk evolution. Taking the inward and outward transportation of materials and evaporation/condensation of silicate at the high temperature midplane region, he reproduced the compositional variation of C-chondrites. Gail [e.g., 3] made extensive work on disk physical evolution combining detailed mineralogy sometimes including organics, and showed mostly high temperature material distribution in disk. The concept is the Euler flow, which gives total variations.

Recent finding of CAIs and chondrules in comet samples, however, suggests transportation of materials formed at the inner edge of the disk was transported to far region. Thus, the Lagrangean treatment would be preferable to understand the dynamics of disk evolution, which is in particular important when we consider chemistry, because different thermal history generates different chemical change for dust grains.

**Purpose:** In order to understand the physical and chemical evolution of protoplanetary disks with the lagrangean treatment, we have developed a new model. We investigate how the chemical composition of a protoplanetary disk changes with time and space by a model combining physics and chemistry. We tried to constrain the conditions to reproduce the chemical variation of chondrites in terms of major elements, which should have been formed within the early stage of the disk ($t < 2-3 \times 10^{5}$ years) at 2-4 AU.

**Model:** Disk evolution model and particle tracking model by Ciesla [*] are modified to describe the chemical evolution of the disk. The essence of the particle tracking model is a radial advection-diffusion equation, which includes stochastic term to represent the random movement of grains by turbulence. The disk model is conventional alpha-disk. Chemical composition of particles is calculated by chemical equilibrium as a function of temperature and pressure. The particles are small and we assume that equilibrium is easily achieved all through the evolution process.

At first, surface density given as a function of distance from the proto-Sun. The disk is divided into bins from 0 to 100 AU and put $10^5$ grains in each bin from 0.05 to 10 AU, for which chemical equilibrium calculation was performed. Thus, the composition of grains varies as a function of distance from the Sun. It should be noted that the composition is not a simple function of distance, but is a complicated function due to the decrease in both temperature and pressure from the Sun to outward with different dependence on the distance. Then, particles were moved according to the equation and we track all the grains for $10^6$ years. Chemical composition of the bins is obtained by averaging the composition of all the grains transporting at a certain time. The results were compared with that of chondrites.

The disk mass is a parameter, which varied from 0.1 to 1 of the Sun, dust aggregation is not taken into consideration, and no further accretion to the disk is assumed.

**Results and discussions:** The surface density decreases and extends outward with time, which is common for disk evolution models. The decrease becomes conspicuous after $5 \times 10^5$ years. Dust grains transported to $\sim 13$ AU at 105 years, $\sim 50$ AU at $5 \times 10^5$ years, and $\sim 100$ AU at $10^6$ years. Temperature also decreases with time; high temperature region (T$>10^6$K) extended to $\sim 3$ AU at the beginning and retreated to $\sim 4$ AU at $10^5$ years, $\sim 1.5$ AU at $5 \times 10^5$ years, and $\sim 0.5$ AU at $10^6$ years.

The flux of inward and outward dust transportation is significant at the early stage ($t < 10^5$ years) and decayed with time. Grains initially located at 1AU reached $\sim 3$ AU and those in $\sim 5$ AU reached $\sim 25$ AU even in $5 \times 10^4$ years. After $10^6$ years, the amount of dust grains, that is disk gas itself, lowers significantly, but grains initially located at 1 AU reached $\sim 50$ AU or farther.

The chemical composition of dusts located at each bin shows spatial and temporal evolution. Figure 1 shows the chemical composition of the disk as a function of distance from the Sun and its temporal variation. The dust compositions at the early stage is enriched in refractory components and depleted in volatile components, which are more significant in the inner region than the outer region. At $10^5$ years, the degree of refractory enrichment decreases and the degree of variation among locations decreases. The tendency continues over time. It is worth noting that the pattern tends to be flat, which means that the disk composition is fractionated at the early stage and becomes unfrac-
ated with time. This is because fractionated grains that were formed at the inner high temperature regions at the early stage were mostly transported to the Sun and because thermally unprocessed (unfractionated) grains were transported from outer region to inner regions. Protoplanetary disk is more heterogeneous at the early stage and becomes homogeneous with unfractionated composition with time. It should be noted that the chemical fractionation pattern is not a produce of simple partial evaporation of partial condensation, but is a mixing pattern of fractionation to various degrees and unfractionated pattern.

As pointed out by previous workers [1, 3], the chemical fractionation pattern of chondrites is fairly well reproduced by simple physical model but those of ordinary chondrites and enstatite chondrites are hardly reproduced, which needs multiple fractionation processes. Figure 2 compares the calculated patterns and C-chondrites. The compositional patten of CM, CO, and CV chondrites are well reproduced by the model. The calculation conditions are time of $10^4$ years.

As is easily expected, the degree and retention time of chemical fractionation within protoplanetary disk should be controlled by the temperature profile of the disk, which is further controlled by the mass of the disk relative to the central star. We have made the same calculations as Fig. 1 with different disk mass and compared the elemental abundance patterns of chondrites. Figure 3 summarizes the suitable conditions to reproduce chondrite composition variations at the asteroidal belt. It is shown that the very early stage of the disk ($t<10^4$ years) could reproduce the chondrite compositional variations. If the disk is heavier, the time for reproduction is earlier.

Although chondrites are believed to have formed at $\sim 10^6$ years or later, the present work showed that much earlier formation is preferable in order to retain chemical heterogeneity. If it is the case, chondrules formation should be a secondary process that took place on the parent body.