TEMPORAL AND SPATIAL EVOLUTION OF THE PROTO-SOLAR DISK: SILICATES, ICE, AND OXYGEN ISOTOPIC COMPOSITIONS.

H. Nagahara[1] and K. Ozawa[2].
[1]Dept.. Earth Planet. Sci., The Univ. Tokyo, Hongo, Tokyo 113-0033, Japan. hiroko@eps.s.u-tokyo.ac.jp.
[2]Dept.. Earth Planet. Sci., The Univ. Tokyo, Hongo, Tokyo 113-0033, Japan. ozawa@eps.s.u-tokyo.ac.jp

Introduction: Transportation of water (ice) in protoplanetary disks is one of the hot topics of planetary science, which is thought to be directly related to the distribution of habitable planets in exoplanetary systems [e.g., 1-3]. However, if we consider the total water content of the Earth (0.02 wt. %), it is easily expected that the transportation of ice in protoplatary disks is not directly related to the habitability of a planet, which is rather the issue of late veneer or early evolution of the surface environments.

The inner planets of our solar system are basically dry, and most of meteorites are also dry. Only very minor fraction of carbonaceous chondrites is wet. CI chondrites are totally hydrated and CM chondrites are mostly hydrated, and CI chondrite alone has relative elemental abundances corresponding to the photosphere of the Sun. Other chondrites are more or less chemically fractionated; chemical fractionation pattern of CM and CO chondrites are fairly well reproduced with the concept of volatility, but that of ordinary chondrites are hardly reproduced [4].

CI chondrites have a unique oxygen isotopic composition, which is also one of most intensively studied issues in planetary material science in these three decades. The oxygen isotopic composition of CI chondrites is heavier than other chondrites and fairly close to the terrestrial fractionation (TF) line.

Present work: We consider the physical and chemical evolution of the proto solar disk (PSD) with special interests to the temporal and spatial evolution of the disk in terms of chemistry and oxygen isotope. The concept of the model is the same as [5], which is standard disk model with turbulent particle movement. We consider more various primitive material distribution and different initial physical and chemical condition of the disk from [5]. The details are shown below.

Primitive materials and their distribution: Recent our study on the Antarctic micrometeorites that are thought to be pristine cometary dusts has revealed that they are a mixture of GEMS (amorphous silicates with Fe metal and pyrrhotite), mostly tiny olivine and pyroxene crystals, and rare large (um in order) crystals, which are embedded in organic materials [6]. These materials form a loose aggregate and are highly porous, which is consistent with the exiting observation by the Rosetta mission. The micrometeorites record the process of early stage of aqueous alteration in primitive bodies; formation of very small amount of liquid water, which may include CO2, NH3, or other ices, resulted in the reaction with organic materials to change their structure and composition to be aromatic ones. Then, also at ~0 °C, liquid water reacts with GEMS instantaneously to form Mg-amorphous silicate and Fe-phyllosilicate (saponite) by consuming Fe metal. The hydrated and anhydrous silicates, FeS, organics, and water further reacted to form Mg-phyllosilicate, carbonates and hydroxide or magnetite at temperature a little above zero. A complex grain model by [7] for dusts in protoplanetary disks consists of silicate core and ice mantle with organics in between them. The intimate coexistence of silicate, organics, and ice well explains the low temperature reaction we have observed.

The exact chemical composition of the silicate portion is hard to be analyzed due to the porous nature; they should have elemental ratios of the solar abundance, because they originated in the extremely low temperature of the prestellar core to protostellar core environments. The relative abundances among silicates, organics, and ice could be variable.

In addition to the primitive components described above, there are larger sized materials including CAIs and various inclusions that are thought to have condensed at temperature above ~1300K.

Physical structure of the disk: [8] discussed that the protostellar core before protoplanetary disk was heated to T>100K within 10AU, where evaporation of some ice and various chemical reaction or organics took place. The inner edge was heated up to above ~1000 K, and the 273K region extends to ~10 – 20 AU in ~10^5 years, which suggests that the initial condition of the disk be divided into three zones: the inner most region was heated up and condensation of mineral took place, the middle region is the place where silicate from the prestellar core remained, but where organics and ice were evaporated. Silicates may have partly changed the composition and size depending on the distance from the Sun. The outer region contains silicate-organics-ice complex grains with chondritic silicate composition. The complex grain changes mineralogy at T>273K, where phyllosilicates were formed as a stable phase, though amorphous silicate was dominant at T<273K. The phyllosilicates loses water at T>~600K. The disk viscosity is a free parameter

Oxygen isotopes: The CAIs, AOAs, and large grains have ^{16}O rich composition, for which we assume to be -50 ‰. The complex low temperature materials have the same composition as the CI on the three oxygen isotope plot, because we consider that the CI s are the remnant of comets formed at the outer region of the disk. We tentatively assume to be δ^{18}O~ + 16‰ and δ^{17}O~ + 9‰, but these numbers may be heavier. When silicates were heated at T>600K and water was lost from phyllosilicates, their oxygen isotopic composition is mass fractionated due to evaporation.

Transpiration and mixing: We assume that all the materials move with gas according to [9], who discussed that even 1cm size objects move together with gas. Due to migration to the star and turbulence, all the solid materials move both inward and outward, and therefore, the mixing ratio of the components varies with time and space. We trace the trajectory of individual grains and calculate, and we know the number of grains with different chemical compositions. By summing up all the grains at a certain time and space, we obtain the bulk chemical composition and oxygen isotopic composition for that space.

Results: A significant amount of grains initially located at the inner region was transported to the outer region, and the farthest grain was transported beyond ~100 AU in 10^6 years originating from 0.5 AU. Figure 1 shows the maximum temperature of experienced temperature of individual grains for initial locations of 0.5 and 20 AU. The 0.5 AU grains are CAIs with oxygen isotopic composition of -50 ‰. The 20AU grains are the complex silicate-organics-ice grains with the oxygen isotopic composition of CI on the three oxygen isotope plot.

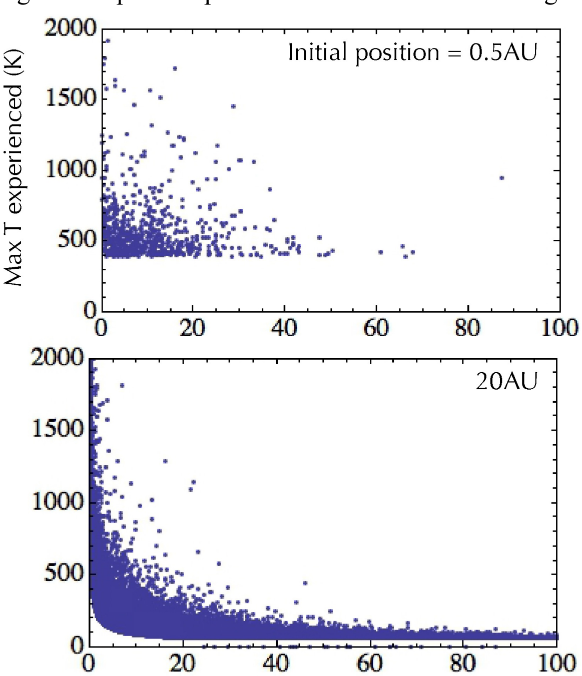

Fig. 1 Maximum temperature that individual 10000 grains experienced during transportation in the disk in 10^6 years. Most of the grains were lost to the Sun. (upper) initial location is 0.5 AU, which are CAIs. (upper) initial location is 0.5 AU, which are CAIs. (lower) initial location is 20 AU, which are initially complex silicate-organics-ice grain. Horizontal is the final location (AU)

The key is the distribution of grains remaining at low temperature, which have heavy oxygen isotopic composition. Mixing of grains in Fig. 1 upper panel and lower panel means the mixing of chondrules, fine-grained dust with solar abundance composition, and silicate-organics-ice complex grains, which reproduces CM and CO chondrites.

Figure 2 shows the temporal and spatial distribution of maximum T=400K and 300K grains. The maximum temperature of 300K grains that keeps primitive nature distributes at 10-20AU in 10^4 years, and largely towards outer region of the disk after that. This result indicates that the oxygen isotopic mixing with ^{16}O-rich materials from the inner region and the primitive material takes place more easily at the early stage of the disk evolution. This is consistent with early stage (<10^5 years) formation of planetesimals, which has been suggested by many authors [e.g., 2]. However, in order to reproduce the oxygen isotopic composition of bulk CV chondrites, mixing of the three components need to be t>10^6 years, otherwise the primitive materials with heavy oxygen isotope are not supplied.

The present model has not yet succeeded in reproducing ordinary chondrites in terms of both bulk chemical composition and oxygen isotopic composition. Another oxygen isotopic component may be required.

References [1] Raymond et al. (2004) *Icarus* **168**, 1. [2] Mulders, G. D. et al. (2015) *arXiv*:1505.03516. [3] Morbidelli, A. et al. (2015) *Icarus* 2015.11.027. [4] Cassem P. (1996) *MaPS* 31, 793. [5] Nagahara, H. et al. (2015) *LPSC*. [6] Noguchi et al. (2016) *LPSC* #1426. [7] Greenberg, M. (1989) IAU Colloq. Interstellar Dust. 345. [8] Aikawa, Y. et al. (2008) *ApJ* 674:993. [9] Johansen, A. et al. (2015). *arXiv*:1505.0294.

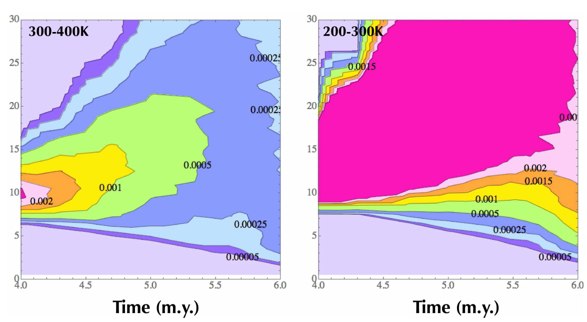

Fig. 2 Temporal and spatial distribution of the grains experienced low temperature for 10^6 years. (Left) Maximum temperature = 400K, and the initially silicate-organics-ice grains are partly converted to silicate alone. (Right) Maximum temperature=300K, and the grains keeps primitive assemblage and heavy oxygen isotopic composition.