MATERIAL TRANSPORT AND OXYGEN ISOTOPIC FRACTIONATION IN THE PROTOSOLAR DISK.

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Introduction: Large scale material transport in protoplanetary disks has been proved by finding of high temperature components in comet Wild 2 [1,2], and it has been supported also by physical models [e.g., 3-7]. Model calculations have shown that solids with micron to mm size are transported to the giant planet region in 10^4–10^5 year at the early stage of the star formation (the accretion rate of 10^{-6}–10^{-7} of the solar mass) and the transport distance becomes shorter with lowering accretion rate. Although outward transport of high temperature products formed at the inner edge of the disk has been discussed extensively, more significant amount of materials was transported inward during accretion stage of the proto-sun. The outward transport of high temperature products and inward transport of materials formed in the precursor molecular cloud should have resulted in chemical and isotopic mixing of the two components, which may be responsible for chemical variation of chondrites. Although several trials have been made for chondrite compositions [8,9], quantitative explanation has not yet been succeeded, which may be due to insufficient understanding of behavior of Mg-Si-Fe, the most fundamental elements of solid planets. As a course of through understanding of physic-chemical evolution of protoplanetary disks, we focused on oxygen isotopic evolution of the disk materials, which is reactive and can be a good tracer for disk evolution.

Oxygen isotopic exchange: Recent high precision analysis with high spatial resolution by ion microprobes has revealed that the variations are a mixture of isotopic mixing and mass-dependent isotopic fractionation [e.g., 10]. Isotopic mixing and mass-dependent fractionation are complicatedly related, one earlier than the other in some cases and vice versa in other cases.

It should be noted that isotopic mixing with two (or more) components with different composition in three oxygen plot does not necessarily form a straight mixing line if evaporation or condensation take place in protoplanetary disks, where total pressure is as low as 10^{-4} bar or lower in most regions. Isotopic mixing is a physico-chemical process that is more effective at higher temperatures, when evaporation or condensation of some components should take place at low pressures. Nagahara and Ozawa [11] investigated the role of isotopic exchange in a protoplanetary disk conditions, where dust and gas with different oxygen isotopic compositions were heated. They have shown that high abundance of ambient oxygen-bearing gas relative to solid components and high isotopic exchange efficiency are required in order to form straight mixing line. Unless the two conditions are satisfied, mixing line would be curved to ^{18}O-richer side of a straight mixing line. The dust/gas ratio to form a straight mixing line is dependent on the initial compositions of gas and dusts, but roughly more than two orders of magnitude abundance of gas is necessary. Thus, oxygen isotope straight mixing lines of meteorites in the three-isotope plot are good indicators of physico-chemical conditions of their formation.

Model: In order to understand material transport and oxygen isotopic characteristics recorded in meteorites in a protoplanetary disk, we have developed a model that describes mixing of two components, one transporting outward from the inner edge and one transporting inward by accretion of a protoplanetary disk with different oxygen isotopic compositions. We assume that the proto-sun had ^{16}O-rich composition ($\delta^{17}O = \delta^{18}O \sim -50‰$) as suggested by the Genesis mission [12], which is shown by refractory inclusions and forsterite grains in primitive chondrites. The "planetary composition" is represented by the Earth ($\delta^{17}O = \delta^{18}O \sim 0‰$) with slight deviation as Mars and asteroids. The materials from outer region were assumed to have oxygen isotopically heavy composition, which we tentatively assume to be that observed in magnetite in a unique carbonaceous chondrite ($\delta^{17}O= \delta^{18}O \sim +200‰$) [13].

The disk has a temperature gradient, and therefore high temperature materials condensed at high temperature of the inner region exchanged oxygen isotopic composition during outward transportation. The "planetary" oxygen isotopic composition suggests that the cessation of isotopic mixing was at around 1 to 2 A.U.

The model investigates isotopic trajectory of solid materials condensed at high temperature region with proto-Sun composition, which changed the composition by isotopic exchange in gas with heavy oxygen isotope composition. The solid materials cool exponentially with time. The system has the composition of the solar abundance elemental rations except for H_2O as a source of heavy oxygen isotope in gas; isotopic exchange is temperature dependent; material transport flux is a steady state. The model contains two free parameters; one is cooling rate and the other is isotopic mixing rate.

Results and Discussions: Figure 1 shows the evolution of oxygen isotopic composition shown as $\delta^{18}O$ of solid materials condensed at a high temperature region and cooled by outward transportation in gas with heavy oxygen isotopic composition with a fixed cooling rate of 0.0001 (dimensionless). The curves are for different mixing ratios of gas and solids. The evolution curves become isotopically heavier with time due to isotopic exchange, and the time of the start of the increase is shorter and the final composition becomes heavier when the mixing rate is large (the blue curve). The time of the increase of the heavy isotope becomes later and the final composition becomes isotopically lighter with decreasing mixing rate. Considering that the "planetary" composition of oxygen isotopes is $\delta^{18}O=0$ by definition, the most plausible mixing rate is 0.00035, the orange curve. We have confirmed that the mixing lines on the three oxygen isotopic plot are straight for both solids and gas, which means that the solid changed its composition from -50‰ to 0‰ and that the gas from +200‰ to 0‰.

A plausible range of the mixing rate was obtained for a range of cooling rates. The mixing ratio of solids with light oxygen and gas with heavy oxygen and cooling rate are linearly related in logarithmic plots. In other words, more abundant low temperature component with heavy oxygen is required if the solid materials cool rapidly. The model results are converted to the real scale for forsterite grains condensing in light oxygen gas, which moves outward, cools, and exchanges oxygen isotopes with ambient gas with heavy composition (Fig. 2). "Cooling rate" of the model corresponds to advection or diffusion rate at the midplane and "mixing rate" corresponds to the ratio of inward flux of isotopically heavy water ice to outward flux of high temperature condensates with light oxygen isotopes. Larger values of "cooling rate" and "mixing rate" may be realized at the early stage of disk evolution.

In summary, "planetary" oxygen isotopes ($\delta^{18}O=0$) were achieved through the evolution of the disk due to larger inward and outward transportation of materials and ice at the early stage and smaller transportation at the later stage.

References: [1] Brownlee, D. et al. (2006) *Science, 314,* 1711-1716. [2] Zolensky, M. et al. (2006) *Science 314,* 1735. [3] Gail H. P. (2001) *A & A 378,* 192-213. [4] Wehrstedt and Gail H. P. (2002) *A & A 385,* 181-204. [5] Tscharnuter and Gail (2007) *A & A 463*, 369-392. [6] Ciesla, F. J. (2007) *Science 318*, 613-615. [7] Yang L. and Ciesla, F. J. (2012) *Metoerit. Planet. Sci. 47*, 99-119. [8] Cassen, P. (1996) *Metoerit. Planet. Sci. 31*, 793-806. [9] Ciesla, F. J. (2008) *Meteori. Planet. Sci. 43*, 639-655. [10] Kita, N. T. et al. (2010) *Geochim. Cosmochim. Acta 74*, 6610-6635. [11] Nagahara and Ozawa (2012) *Meteorit. Planet. Sci. 47*, 1209-1228. [12] McKeegan, K. D. et al. (2011) *Science 332*, 1528-1532. [13] Sakamoto, N. et al. (2007) *Science 317*, 231-233.

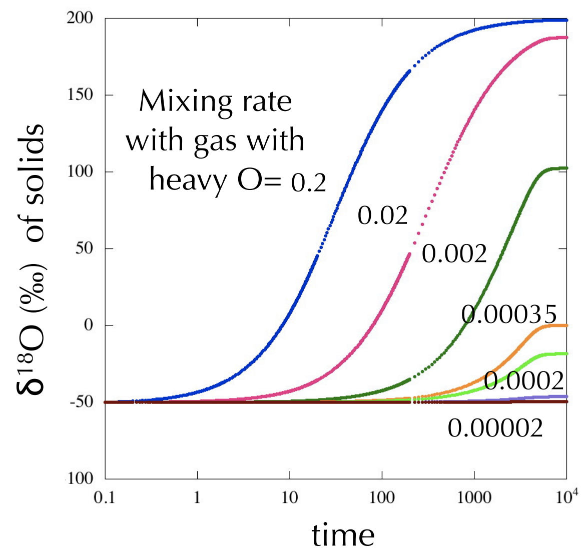

Fig. 1 Evolution of oxygen isotopic composition of solids initially with d18O=-50‰, which were transported to outer lower temperature region and exchange isotopic composition with gas with $\delta^{18}O=-200$‰ (cooling rate=0.0001). Depending on the mixing rate, the time to start and complete isotope exchange and final isotopic composition varied.

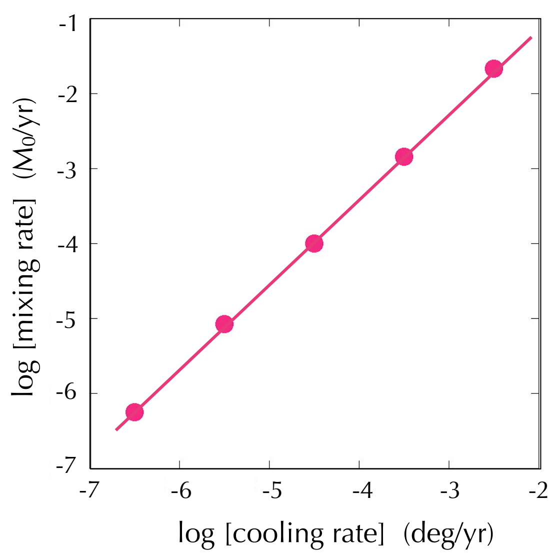

Fig. 2 Conditions for achievement of the "planetary" oxygen isotopic composition ($\delta^{18}O=0$‰) by isotopic mixing of forsterite grain initially with $\delta^{18}O=-50$‰, which was condensed at 1300K at 10^{-4} bar and low temperature component (H_2O gas) with d18O=-200‰. M_0 of the vertical represents initial mass of the gas with $\delta^{18}O=-50$‰, which corresponds the amount of condensates.