RADIAL MIGRATION OF MATERIALS FROM INNER TO OUTER SOLAR NEBULA: EVIDENCE FROM METEORITE MATRIX. H. Yurimoto, K. Nagashima, and H. Emori, Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan (yuri@geo.titech.ac.jp),

Introduction: Outward migration of material in the accreting solar nebula has been predicted by astrophysical models [1,2] and is considered a plausible mechanism to explain crystalline silicates in comets [3,4]. Although solar nebular processes are recorded in primitive meteorites, direct evidence indicating outward migration has not been found, partly because forming places of meteoritic constituents are still controversial [5,6]. Here we report ^{16}O-rich enstatite micro-objects coexisting with carbonaceous presolar sub-micro-grains in the matrix of a primitive meteorite using *in-situ* high-precision isotope imaging, indicating evidence of the migration.

Experimental: The sample used in this study is a polished thin section from NWA-530 CR2 chondrite. Petrologic and mineralogical studies by scanning electron microscope (JEOL JSM-5310LV) equipped with energy dispersive X-ray spectroscopy (Oxford LINK ISIS) were made before and after the isotope analysis. High resolution back scattered electron (BSE) images are obtained by JEOL JSM-6500F scanning electron microscope at the JEOL Application Lab.

Oxygen isotopic analyses were performed by TiTech isotope microscope system (CAMECA IMS-1270 + SCAPS [7]). The size of a δ^{18}O map corresponds to 70 x 70μm on the sample.

Results and Discussion: Enstatite is usually observed in chondrules as a crystal from ferromagnesian silicate melt in the solar nebula. Isolated enstatite grains of micro to submicro sizes are rarely observed in matrices of chondrites. The oxygen isotopic compositions of isolated enstatite grains vary grain by grain from ^{16}O-poor near-chondrule values [8] to ^{16}O-rich values of refractory inclusions (Fig. 1). The enstatite grains with ^{16}O-poor compositions may have formed by intensive fragmentation of chondrules. However, the ^{16}O-rich enstatite grains are clearly not fragments of chondrules but are linked to refractory inclusions. The ^{16}O-rich enstatite often directly overgrows and envelops olivine grains (Fig. 1). On the basis of condensation theory, enstatite does not condense directly from cooling hot nebular gas of solar composition, but is formed by the solid-gas reaction between precondensed olivine and the cooling nebular gas or by crystallization in precondensed silicate melt in the nebula [9]. The ^{16}O-rich enstatite rimed olivine grains (Fig. 1) are consistent with the solid-gas reaction predicted by the condensation model. The enstatite forming reaction without liquid starts from 1490 - 1190 K under possible nebular total pressure ranges (10^{-3} - 10^{-6} bar).

Because growth rates of the enstatite are controlled by element diffusion in the enstatite layer [10], thermal history of the grain is calculated from the thickness of enstatite layer. Typical thickness of the enstatite layer is 0.5 - 1 μm and is comparable to individual grain sizes of enstatite crystal (Fig. 1). Therefore the ^{16}O-rich enstatite grew under annealing at constant temperature of 10^3 - 10^{-2} years or under the cooling rate of 10^3 - 10^{-1} K/year in the hot nebula. Such long annealing time or slow cooling rate is clearly incompatible with flash heating events forming chondrules but can be realized in the hot nebular region close to the Proto-Sun or to cooling rates of the nebular thermal evolution of the inner disk in T Tauri stage.

On the other hand, carbonaceous pre-solar grains are observed in the matrix from the same chondrite (Fig. 2). The carbon isotopic compositions indicate that the grains formed around stars that preceded the Sun. Carbonaceous presolar grains tend to have undergone volatilization while immersed in the solar nebula. Life times of 1 μm sized interstellar graphite particles in the solar nebula are experimentally estimated to ~7 hours at 1300 K and ~200 hours at 1000 K [11]. Therefore the submicron carbonaceous presolar grains in Fig. 2 cannot survive under the forming conditions of the ^{16}O-rich enstatite grains in Fig. 1. Thus, the nebular thermal evolution cannot account for the coexistence of these objects. The enstatite and carbonaceous presolar grains should have experienced different thermal histories prior to transport into the same nebular region, where they were accreted into a parent body of the chondrite.

The chondrite-forming region is believed in the nebular midplane at ~2.5 AU from the Proto-Sun, where the nebular temperature is 100 to 400 K during a classical T Tauri stage [12]. The carbonaceous presolar grains came directly from a cold molecular cloud to the chondrite-forming region without passing through the hot portion of the solar nebula. In contrast, the hot nebular region with temperatures hot enough to form the ^{16}O-rich enstatite is limited to within ~0.5 AU from the Proto-Sun according to the radial temperature distribution in the solar nebula.

These *in-situ* high-precision isotopic images reveal evidence that ^{16}O-rich enstatite grains formed in the hot nebular region close to the Proto-Sun. Coexistence of the enstatite and carbonaceous presolar grains in the matrix proves that materials in the hot solar nebula close to the Proto-Sun migrated outward at least as far as the chondrite-forming region and mixed with infalling interstellar materials.

The outward migration rates are constrained by the cooling rate of the enstatite objects combined with radial distribution of disk midplane temperatures at a T Tauri stage. The midplane temperature gradient is formulated from Woolum and Cassen [12] under the condition that nebular mass distribution has the same power index to that of the minimum mass solar nebula model as: $dT_m/dr = (-9/8)\ (T_{m(1AU)}/1AU)\ (r/1AU)^{-17/8}$ where $T_{m(1AU)}$ and r are midplane temperature at 1AU and radial distance from the Sun, respectively. This suggests that the temperature gradients at r=0.5 AU are between approximately 50 K/AU and 200 K/AU. Outward migration rates of the enstatite objects are estimated to be 0.1 - 1 and 10^3 - 10^4 years/AU at starting temperatures of enstatite growth of 1490 K and 1190 K, respectively. The slower migration rates are comparable to those of turbulent radial mixing (~10^3 years/AU) [2]. The higher rates are consistent with outward migration of the particles by launch in an X-wind process [1]. In either case, coexistence of the enstatite and carbonaceous presolar grains demonstrates that global radial mixing of dusts in the solar nebula occurred in the T Tauri stage. Although abundances of confirmed inner nebular grains found in the primitive meteorite are minor, this is a minimum estimate because other chondrite components also might have originated in the inner disk. Furthermore, nebular grains can easily be destroyed by subsequent aqueous and thermal metamorphism after accretion to the planetesimal. Evidence for radial migration of materials in the solar nebula observed in meteorites demonstrates that such global dust mixing must be considered to explain not only abundant crystalline silicates with solar isotopic composition in comets or in Edgeworth-Kuiper Belt objects [13], but also the chemical variation among terrestrial planets.

References: [1] Shu F. H. et al. (1996) *Science*, **271**, 1545. [2] Bockelee-Morvan D. et al. (2002) *Astron. Astrophys*. 384, 1107. [3] Crovisier J. et al. (1997) *Science*, **275**, 1904. [4] Hanner M. S. (1999) *Space Sci. Rev*., **90**, 99. [5] Alexander C. M. O'D. et al. (2001) Science, 293, 64. [6] Itoh S. and Yurimoto H. (2003) *Nature*, **416**, 39. [7] Yurimoto H. et al. (2003) *Appl. Surf. Sci*., **203-204**, 793. [8] Kunihiro T. et al. (2003) *GCA*, submitted. [9] Ebel D. S. and Grossman L. (2000) *GCA*, **64**, 339. [10] Imae N. et al. (1993) *EPSL*, **118**, 21. [11] Mendybaev R. A. et al. (1997) *LPS* 28, 937. [12] Woolum D. S. and Cassen P. (1999) *M&PS*, **34**, 897. [13] Messenger S. et al. (2003) *Science*, **300**, 105.

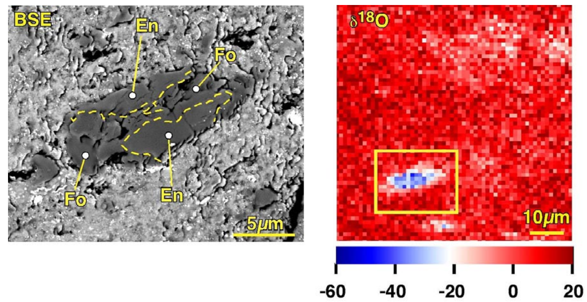

Fig. 1. Enstatite micro-objects in matrix of a primitive meteorite. An olivine (Fo) grain partially covered by a thin layer of enstatite (En). The grain is enriched in ^{16}O of $\delta^{18}O_{SMOW}$ = ~-33‰. Errors of the δ-values are estimated to 6-7‰ for each pixel. A yellow square in the isotopograph corresponds to the BSE fields.

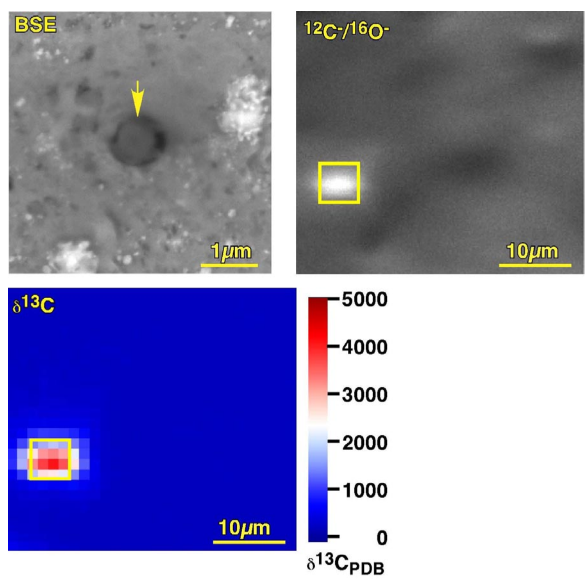

Fig. 2. Carbonaceous presolar grains in matrix of a primitive meteorite. A submicro-graphite grain shown by arrow with extreme enrichment of ^{13}C ($\delta^{13}C_{PDB}$ = 4230±8 (1σ)). Yellow squares in isotopographs correspond to the BSE fields.