AL−MG SYSTEMATICS OF NEBULAR CONDENSATES IN THE EFREMOVKA CV3 CHONDRITE.
N. Kawasaki[1] and H. Yurimoto[2, 1], [1]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara 252-5210, Japan. (kawasaki@planeta.sci.isas.jaxa.jp), [2]Natural History Sciences, Hokkaido University, Sapporo 060-0810, Japan.

Introduction: Ca-Al-rich inclusions (CAIs) in meteorites, the oldest objects in the Solar System determined by U-corrected Pb−Pb absolute chronology [1], are considered to have formed near the protosun [2–4]. Many CAIs contained live ^{26}Al, a short-lived radionuclide with a half-life of 0.705 Myr [5], at their formation [6, 7]; ^{26}Al–^{26}Mg systematics have been widely used for early Solar System chronology [8]. Recent high-precision ^{26}Al–^{26}Mg mineral isochron studies using secondary ion mass spectrometry (SIMS) offer detailed distributions of initial ^{26}Al/^{27}Al values, $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0$, for individual CAIs and chondrules [e.g. 8–11]. Melted coarse-grained CAIs with igneous textures tend to have lower $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0$ than un-melted CAIs, nebular condensates: un-melted CAIs exhibit consistent values of $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0 \sim 5.2 \times 10^{-5}$, while $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0$ of the melted CAIs range from ~5.2 to ~4.2 $\times 10^{-5}$, corresponding to a formation age spread of ~0.2 Myr [9]. Recently, $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0$ of reversely zoned melilite crystals, which are considered to be nebular condensates with no signatures of later melting [12], in a fluffy Type A CAI from Vigarano, V2-01, were determined as $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0 = (4.69 \pm 0.13) \times 10^{-5}$ [10], which corresponds to intermediate values among the values for melted CAIs [9]. Because there are few studies with such high-precision ^{26}Al–^{26}Mg mineral isochrons for individual CAIs, here we provide new constraints on variations in CAIs formation age using SIMS. Newly obtained ^{26}Al–^{26}Mg mineral isochrons for two nebular condensates from the Efremovka CV3 chondrite, a Type A CAI, HKE01, with known O isotopic distributions for melilite crystals [13], and a fine-grained CAI, HKE02, are presented.

Experimental: Both the CAIs are included in the same polished thin section of Efremovka (Fig. 1). Backscattered electron imaging, quantitative elemental analyses, and X-ray elemental mapping were conducted using field emission type scanning electron microscopes with energy dispersive X-ray spectrometers (JEOL JSM-7000F with Oxford X-Max 150 at Hokkaido University and Hitachi SU6600 with Oxford X-Max 20 at ISAS/JAXA). The ^{26}Al–^{26}Mg systematics of the CAIs were conducted using a SIMS instrument (Cameca ims-1280HR at Hokkaido University). Detailed measurement conditions with SIMS have been described elsewhere [10].

Results and Discussion: The fine-grained CAI, HKE02 (Fig. 1b), is composed mainly of spinel, melilite, and diopside, and rarely of anorthite and perovskite. The irregular shape of the CAI indicates it is likely a nebular condensate. The Al−Mg isotopic compositions of the spinel and melilite were measured (Fig. 2); the obtained ^{26}Al–^{26}Mg mineral isochron gives $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0 = (5.26 \pm 0.26) \times 10^{-5}$ and $(\delta^{26}\mathrm{Mg}^*)_0 = -0.014 \pm 0.074$ ‰. These are essentially identical to the canonical values determined by whole-rock ^{26}Al–^{26}Mg isochron studies for CAIs (±amoeboid olivine aggregates) [14, 15] as well as the initial values for the un-melted CAIs, the nebular condensates [9, 16].

The Type A CAI, HKE01 (Fig. 1a), is composed of two domains divided by the Wark-Lovering rim [17], which grew in nebular reservoirs with distinct O isotopic compositions, temperature and/or pressure [13]. Each domain has a core-mantle structure. At one of the two domains, the mantle consists mainly of numerous reversely zoned melilite crystals, which are likely aggregated nebular condensates, similar to general features of fluffy Type A CAIs [18]. Melilite crystals showed continuous variations of O isotopic compositions from ^{16}O-rich ($\Delta^{17}\mathrm{O} \sim -20$ ‰) to ^{16}O-poor ($\Delta^{17}\mathrm{O} \sim -5$ ‰). Isotopic compositions tend to be more ^{16}O-rich toward the domain rim, suggesting that the melilite crystals condensed from the nebular gas with a variable O isotope reservoir changing from ^{16}O-poor to ^{16}O-rich [13]. The Al−Mg isotopic compositions of the melilite

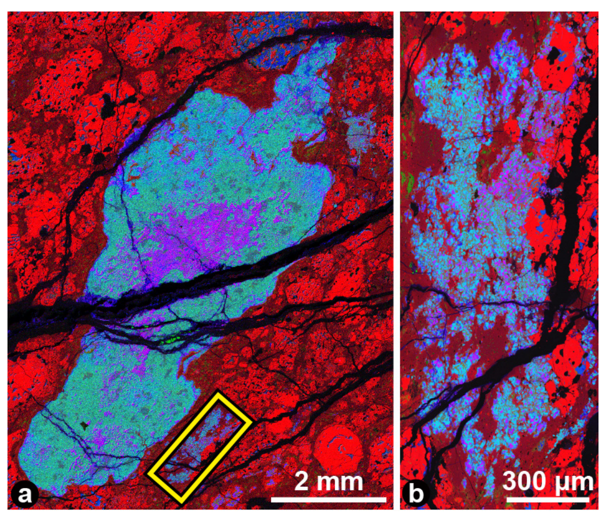

Fig. 1. Combined X-ray elemental map of (a) Type A CAI, HKE01 and (b) fine-grained CAI, HKE02, from Efremovka, with Mg (red), Ca (green), and Al (blue). Yellow box in (a) indicates the area shown in (b).

crystals were measured; an isochron gives $(^{26}Al/^{27}Al)_0 = (4.52 \pm 0.15) \times 10^{-5}$ and $(\delta^{26}Mg^*)_0 = -0.10 \pm 0.14$ ‰. The $(^{26}Al/^{27}Al)_0$ of HKE01 is equivalent to the $(^{26}Al/^{27}Al)_0$ for reversely zoned melilite crystals in the V2-01 Vigarano fluffy Type A CAI, $(4.69 \pm 0.13) \times 10^{-5}$ [10].

The bulk $^{27}Al/^{24}Mg$ ratio of the HKE01 CAI is ~4.6. We calculated a Mg isotope evolution of HKE01 (Fig. 3) using a procedure similar to those used by [9, 19]. Given that the bulk Al/Mg chemical fractionation for HKE01 occurred at the canonical age, the Mg isotopic composition of HKE01 would have evolved with the composition of $^{27}Al/^{24}Mg \sim 4.6$. In this case, $(\delta^{26}Mg^*)_0$ would be 0.22 ± 0.06 ‰ for HKE01 by resetting of the Al−Mg system at $(^{26}Al/^{27}Al)_0 = (4.52 \pm 0.15) \times 10^{-5}$. This value, 0.22 ± 0.06 ‰, is clearly higher than the $(\delta^{26}Mg^*)_0$ of -0.10 ± 0.14 ‰ for the melilite crystals in HKE01. These differences strongly suggest that the chemical Al/Mg fractionation of HKE01 is unlikely to have occurred at the canonical age. Rather, the Mg isotope system of the reversely zoned melilite crystals of HKE01 likely evolved in a solar composition nebular gas with $^{27}Al/^{24}Mg = 0.101$, from which they condensed, consistent with their inferred condensation origin from the nebular gas [13].

The initial $^{26}Al/^{27}Al$ values for the observed nebular condensates (HKE02 fine-grained CAI, reversely zoned melilite crystals in HKE01 Type A CAI, and melilite crystals in V2-01 fluffy Type A CAI [10]) range from (5.26 ± 0.26) to $(4.52 \pm 0.15) \times 10^{-5}$. This range corresponds to a formation age spread of 0.15 ± 0.06 Myr, which is similar to the formation age spread for the melted CAIs of ~0.2 Myr [9]. These data imply that un-melted CAIs formed contemporaneously with melted CAIs in solar composition gas during ~0.2 Myr from the canonical age.

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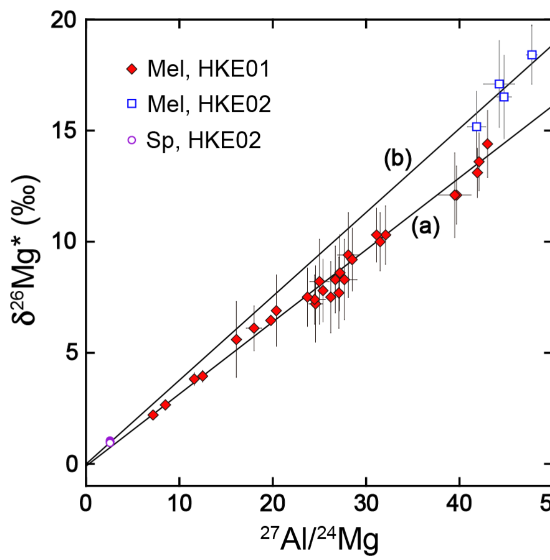

Fig. 2. ^{26}Al–^{26}Mg isochrons for nebular condensates from Efremovka. (a) Reversely zoned melilite crystals in HKE01, $(^{26}Al/^{27}Al)_0 = (4.52 \pm 0.15) \times 10^{-5}$ and $(\delta^{26}Mg^*)_0 = -0.10 \pm 0.14$ ‰. (b) HKE02, $(^{26}Al/^{27}Al)_0 = (5.26 \pm 0.26) \times 10^{-5}$ and $(\delta^{26}Mg^*)_0 = -0.014 \pm 0.074$ ‰. Errors are 2σ. Mel, melilite; Sp, spinel.

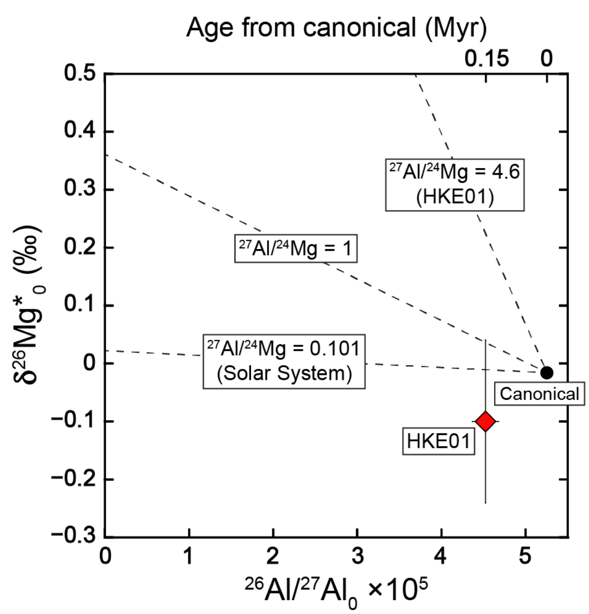

Fig. 3. Magnesium isotope evolution of HKE01. Dashed lines indicate Mg isotope evolution paths for each $^{27}Al/^{24}Mg$ ratio from the canonical Al−Mg isotopic compositions depicted by a solid circle [15]. The $^{27}Al/^{24}Mg$ ratio of the Solar System is taken from [20].