Mg ISOTOPIC COMPOSITIONS OF FINE-GRAINED Ca-Al-RICH INCLUSIONS FROM REDUCED CV3 CHONDRITES AND IMPLICATIONS ON THE TIMESCALE OF NEBULAR CONDENSATION.

J. Han[1,2], M.-C. Liu[3], N. Matsuda[3], C. Park[4], and L. P. Keller[2], [1]Lunar and Planetary Institute, USRA, 3600 Bay Area Boulevard, Houston, TX 77058, USA (han@lpi.usra.edu), [2]ARES, Code XI3, NASA Johnson Space Center, 2101 NASA Parkway, Houston, TX 77058, USA, [3]Department of Earth, Planetary, and Space Sciences, UCLA, Los Angeles, CA 90095, USA, [4]Division of Earth-System Sciences, Korea Polar Research Institute, 26 Songdomirae-ro, Yeonsu-gu, Incheon 21990, South Korea.

Introduction: Fine-grained Ca-Al-rich inclusions (FGIs) in carbonaceous chondrites are interpreted as aggregates of nebular gas-solid condensates that escaped significant melting [1]. Recent Al-Mg isotopic studies of small FGIs (<200 µm in size) from pristine CO3 chondrites have revealed significant variations in initial $^{26}Al/^{27}Al$ ratio, $(^{26}Al/^{27}Al)_0$, spanning from 5.73×10^{-5} to 8×10^{-6} [2,3]. Importantly, [3] found a main CAI population characterized by $(^{26}Al/^{27}Al)_0 = 5.4\times10^{-5}$ that likely record the onset of dust condensation and initial coagulation events, followed by multiple thermal events over an extended time period. Thus far, a small number of large FGIs from CV3 chondrites have been analyzed, showing a narrower range of $(^{26}Al/^{27}Al)_0 = 5.27\times10^{-5}$ to 3.35×10^{-5} [4-6], similar to those inferred from coarse-grained, igneous CAIs (CGIs) from CV3 chondrites [7]. These observed different ratios may raise a question if large FGIs in CV3 chondrites record a time interval from primary direct condensation of refractory solids to their aggregation and growth into larger inclusions.

In this study, we present Al-Mg isotopic compositions of FGIs from reduced CV3 chondrites to better constrain their formation timescale relative to smaller FGIs in CO3 chondrites, as well as to CGIs in CV3 chondrites. This isotopic study is coordinated with a microstructural study to elucidate the origin and nature of FGIs in the petrologic and mineralogical context.

Methods: Our initial mineralogical and petrologic characterizations of FGIs from the reduced CV chondrites Efremovka and Thiel Mountains (TIL) 07003 were conducted using the FEI Quanta 3D FEG dual beam SEM/FIB and JEOL JXA-8530F electron microprobe at NASA JSC. A detailed microstructural study of two FGIs A-01 and A-02 from Efremovka using the JEOL 2500SE field emission scanning TEM at NASA JSC was reported in [8].

Three FGIs (E-A-01, E-A-02, and E-B-01) from Efremovka and one FGI (TIL 003-02) from TIL 07003 were selected for *in situ* Al-Mg isotope analyses performed in a high-precision multicollection mode on the CAMECA ims-1290 ion microprobe at UCLA. Hibonite, spinel, melilite, and diopside in the FGIs were sputtered with a 1–2 nA $^{16}O_3^-$ primary ion beam generated by a Hyperion-II oxygen plasma source. Our detailed analytical procedure was described in [9].

Results: The four FGIs from Efremovka and TIL 07003 are irregularly-shaped, often elongated inclusions (up to ~4 mm in size) that share the basic internal structure consisting of numerous nodules. None of the FGIs are mineralogically zoned and porous. Most inclusions lack Na-rich and Fe-rich phases of likely secondary parent body alteration origin that are common in FGIs from oxidized CV3 chondrites. Importantly, significant variations in mineralogy, modal abundance, and nodule size and shape among the four FGIs are observed, as described below.

E-A-01 has the typical structure of irregularly shaped nodules of spinel with minor hibonite and perovskite that are surrounded successively by melilite, anorthite, diopside, and forsteritic olivine.

E-A-02 has a simpler mineralogy of nodules consisting of spinel cores surrounded by melilite, anorthite, and diopside. Rare perovskite is present in melilite, but hibonite is absent.

E-B-01 is a hibonite-rich inclusion, in which the cores of individual nodules are dominated by hibonite with minor spinel and perovskite, followed by thin sequential layers of melilite, anorthite, and diopside. Rare grossite occurs associated with a hercynite-like phase.

TIL 003-02 has a similar texture to *E-A-02*. The nodules contain cores of spinel and minor perovskite, surrounded by Al,Ti-diopside, melilite+spinel, intimate intergrowths of spinel+Al,Ti-diopside+perovskite, anorthite, and diopside. The forsterite-rich accretionary rim is partially present on the exterior of the inclusion. No hibonite is observed.

Our high-precision multicollection data of hibonite, spinel, melilite, and diopside in the four FGIs from Efremovka and TIL 07003 yield well-defined isochrons (**Figure 1**), which clearly show variations in $(^{26}Al/^{27}Al)_0$ value among the inclusions. The inferred $^{26}Al/^{27}Al$ ratios are $(5.59\pm0.25)\times10^{-5}$ for E-A-01, $(4.13\pm0.61)\times10^{-5}$ for E-A-02, $(5.18\pm0.19)\times10^{-5}$ for E-B-01, and $(4.83\pm0.50)\times10^{-5}$ for TIL 003-02 (2σ errors). The FGIs have $\delta^{25}Mg$ <1‰ and do not show significant isotopic fractionations.

Discussion: The observed layered structure and fine-grained nature of the Efremovka and TIL 07003 FGIs and the decrease in volatility through mineral layers in their individual nodules confirm that they formed by condensation [1]. Also, their condensation origin is consistent with very low δ^{25}Mg values (<1‰) of the FGI analyzed in this study. The fine scale layering preserved in individual nodules may reflect evolving condensation and gas-solid reactions that grew single grains into layered nodules under non-equilibrium conditions. These replacement reactions clearly did not go to completion, protecting underlying grains from further back reactions [10]. However, remarkable mineralogical and textural variations in individual FGIs indicate distinct formation conditions that enabled each inclusion to have experienced different gas-solid reaction paths. Nonetheless, the FGIs represent primary condensates that had never been re-melted after their initial formation and therefore could still preserve Mg isotopic compositions at the time of condensation in the solar nebula.

Our high-precision multicollection data obtained from the four FGIs in Efremovka and TIL 07003 yield isochrons with a well-resolved spread in $(^{26}Al/^{27}Al)_0$ values, consistent with those obtained from CGIs [7]. In addition, a range of $(^{26}Al/^{27}Al)_0$ values from $(5.19\pm0.17)\times10^{-5}$ to $(3.35\pm0.21)\times10^{-5}$ were inferred from FGIs in Efremovka, Vigarano, and TIL 07007 [5]. Collectively, the observed spread suggests multiple condensation events over a time span of at least ~0.4 Ma to form large FGIs found in CV3 chondrites. This also implies that condensation events occurred contemporaneously with melting events recorded in CGIs [4,7].

The inferred $(^{26}Al/^{27}Al)_0$ values of E-A-01, E-B-01, TIL 003-02 are broadly consistent with the bulk CAI value of $(5.23\pm0.13)\times10^{-5}$ [11]. A consistent $(^{26}Al/^{27}Al)_0$ value of ~5.2×10^{-5} inferred from some FGIs [4,5,7,this study] may define a time zero when most pristine, large FGIs formed by condensation, probably ~40,000 years after primary condensation of small FGIs characterized by $(^{26}Al/^{27}Al)_0 = 5.4\times10^{-5}$ [3]. A larger set of high-precision data obtained from large FGIs in CV3 chondrites is required to test this.

Conclusions: Our high-precision multicollection data obtained from the four FGIs in the reduced CV3 chondrites Efremovka and TIL 07003 yield isochrons with a well-resolved spread in $(^{26}Al/^{27}Al)_0$ values, suggesting multiple condensation events over a time span of at least ~0.4 Ma. These observations imply that the CAI formation by condensation and melting occurred repeatedly and contemporaneously over a short time interval.

Acknowledgments: This study was supported by NASA grant 80NSSC18K0602 to M.-C. Liu and 17-EW17_2-0148 to L. P. Keller.

References: [1] Krot A. N. et al. (2004) MAPS 39, 1517-1553. [2] Simon S. B. et al. (2019) MAPS 54, 1362-1378. [3] Liu M.-C. et al. (2019) Sci Adv 5, eaaw3350. [4] MacPherson G. J. et al. (2010) ApJ 711, L117-L121. [5] Kawasaki N. et al. (2019) MetSoc, #6021. [6] Wada S. et al. (2019) MetSoc, #6028. [7] MacPherson G. J. et al. (2012) EPSL 331-332, 43-54. [8] Han J. et al. (2019) MetSoc, #6435. [9] Liu M.-C. et al (2018) Int J Mass Spectrom 424, 1-9. [10] Petaev M. I. & Wood J. A. (2005) In Chondrites and Protoplanetary Disk, vol.341, pp.373-406. [11] Jacobsen B. et al. (2008) EPSL 272, 353-364.

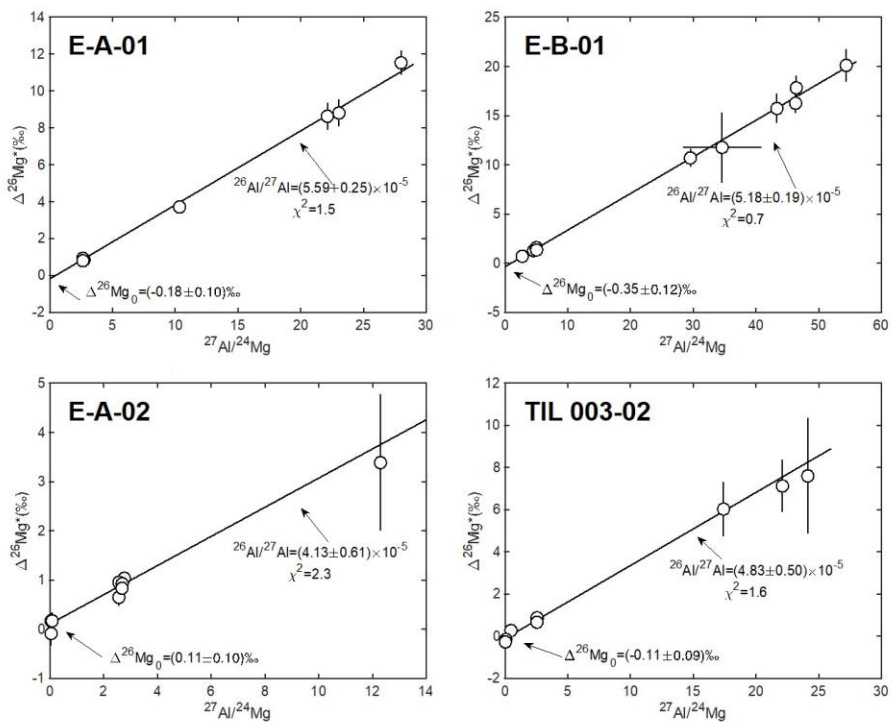

Figure 1. Isochron diagrams of $\Delta^{26}Mg^*$ vs. $^{27}Al/^{24}Mg$ for the four FGIs from Efremovka and TIL 07003.