A COMBINED STUDY OF THE Al-Mg SYSTEMATICS AND O ISOTOPE RATIOS OF CHONDRULES FROM THE PRIMITIVE CARBONACEOUS CHONDRITE ACFER 094.

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Introduction: Chondrules are small igneous silicate spherules and are abundant in primitive meteorites, implying that the melting of silicate particles was a common phenomenon in the solar nebula. The timing of chondrule formation is considered to be 1 to 3 Myr after CAIs according to the inferred initial $^{26}Al/^{27}Al$ ratios [e.g. 1, 2], assuming the Al-Mg systematiccs were not disturbed in the least equilibrated chondrites in the parent body. In this study, we measured Al-Mg systemtatics in type I chondrules from Acfer 094 that we previously measured O isotope ratios [3]. Since Acfer094 is not only the least metamorphosed carbonaceous chondrites (type 3.00) but also absent from hydrated minerals, chondrules from Acfer 094 should be the best samples to examine the primary Al-Mg systematics without isotopic disturbance during metamorphism in their parent body.

Samples and Methods: The Al-Mg systematics of chondrules were measured by Wisc-SIMS, Cameca ims-1280 ion microprobe at University of Wisconsin-Madison. We selected 10 chondrules (8 type I, 1 refractory forsterite (RF) bearing type I, and 1 Al-rich) that have plagioclase crystal of >5 μm in size of the Acfer 094 polished thin section (USNM 7233-8). Oxygen isotopic ratios of 8 out of 10 chondrules have been analyzed by Wisc-SIMS [3]. It has been shown that averaged O isotopic ratios of individual chondrules (excluding minor relict olivine grains) are distributed between the CCAM and Young and Russell lines and are mainly classified into two subgroups of $\Delta^{17}O$~-2 and ~-5 ‰ (Figure 1). Samples in this study contain whole range of observed $\Delta^{17}O$ of chondrules in [3]. It is worth noting that the chondrule G46 contains ^{16}O-poor relict olivine grains and the chondrule G68 has highly heterogeneous O isotopic ratios (-23.0 to -4.0 ‰ in $\Delta^{17}O$; see Figure 2 in [3]).

High intensity primary O^- beam (~4.5 nA) of ~15 μm in diameter was used to measure Mg isotopes of Mg-rich phenocrysts (olivine and pyroxene)(Figure 2b). Secondary ions ($^{24}Mg^+$, $^{25}Mg^+$, $^{26}Mg^+$, and $^{27}Al^+$) were detected by multiple Faraday cup (FC) detectors, simultaneously. For Mg isotope analyses of plagioclase, we used lower intensity primary O^- beam (~70 pA) of ~5 μm in diameter. Secondary Mg ions were detected by an axial electron multiplier (EM) with a magnetic peak switching (Figure 2c). Secondary Al ions were detected by one FC on multiple detector trolleys during $^{25}Mg^+$ measurement by an axial EM. Analytical conditions and data reductions of multiple-FC and axial-EM analyses are similar to those described in [4] and [5], respectively. San Carlos olivine and synthetic anorthitic glass of 1 wt% were used for running standards. Typical errors (2SD) of $\delta^{26}Mg$ are ±0.05 ‰ for olivine and pyroxene and ±0.9 ‰ for plagioclase, respectively.

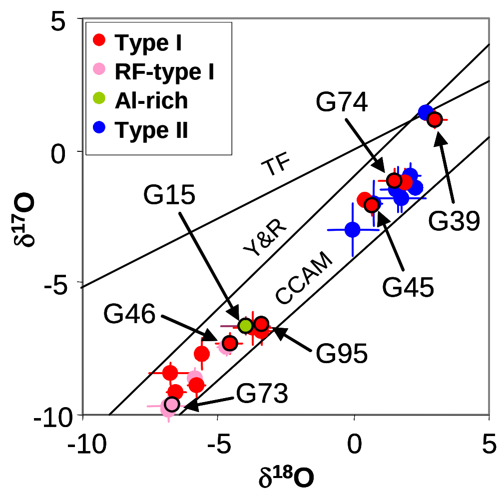

Figure 1. Averaged O isotope ratios of chondrules from Acfer 094. Three reference lines are the terrestrial fractionation (TF), CCAM, and Young&Russell (Y&R) lines, respectively. Errors are 2SD.

Results and Discussion: We performed 2-4 Mg isotope analyses of Mg-rich phases (olivine and pyroxene) and plagioclase of individual chondrules, respectively, to obtain internal isochrone (e.g. Figure 2d). The $^{27}Al/^{24}Mg$ ratios of plagioclase are 27 to 55 and all the measured chondrules preserve significant ^{26}Mg excess in plagioclase (up to 3.3 ‰). Inferred initial $^{26}Al/^{27}Al$ ratios of chondrules are from $(9.0\pm1.5)\times10^{-6}$ to $(4.2\pm2.0)\times10^{-6}$ and those of 6 out of 8 chondrules are identical (~5×10^{-6}) within 2SD error (Figure 3). These values are within a range of observed initial $^{26}Al/^{27}Al$ ratios of chondrules from Acfer 094 [6, 7].

Initial $^{26}Al/^{27}Al$ ratio vs. $\Delta^{17}O$. There is no correlation between initial $^{26}Al/^{27}Al$ ratios and the averaged O isotopic ratios of chondrules from Acfer 094. Initial $^{26}Al/^{27}Al$ ratios of chondrules of two subgroups (averaged $\Delta^{17}O$~-2 and ~-5 ‰) overlap each other. Difference in $\Delta^{17}O$ of chondrules suggests existence of O isotopic heterogeneity of ambient gas where chondrules formed. Identical initial $^{26}Al/^{27}Al$ ratios of chondrules suggest that chondrules record local O isotopic heterogeneity in the solar nebula when chondrules formed instead of temporal change of O isotope ratios of nebular gas. Initial $^{26}Al/^{27}Al$ ratios of 3 chondrules (G45, G46, and G68) that contain relict olivine grains with anomalous O isotope ratios are identical to those of other chondrules. Although O isotope ratios of G68 are highly heterogeneous and ^{16}O-rich (up to $\Delta^{17}O$=-23 ‰) suggesting a close relation to CAIs or AOAs, the chondrule G68 is as young as other chondrules from Acfer 094. Chondrules containing abundant ^{16}O-rich relict olivine grains are not older than other chondrules, though they are probably less processed than others.

Initial $^{26}Al/^{27}Al$ ratio of chondrules among different chondrites. Because type I chondrules are majority (~80 %) of chondrules of Acfer 094, inferred initial $^{26}Al/^{27}Al$ ratios of 5×10^{-6} would be a typical value of chondrules from Acfer 094. This value is somewhat lower than those of chondrules from UOCs [e.g. 1, 8-10] and CO3.0 [5] but higher than those of chondrules from CR2 chondrites [11]. Assuming homogeneous ^{26}Al distribution in the solar nebula [9, 12, 13], difference in initial $^{26}Al/^{27}Al$ ratios of chondrules from different chondrites suggests that timing of peak (or cease) of chondrule formation vary regionally in the solar nebula. Higher initial $^{26}Al/^{27}Al$ ratios observed in 2 type I chondrules of this study and plagioclase-rich chondrules (up to $14.5\pm4.8\times10^{-6}$) [6] suggest that chondrules formed at different timing accreted into a single chondritic parent bodies. For better understanding of duration of chondrule formation, further studies on the Al-Mg systematics of type II chondrules from Acfer 094 would be required since type II chondrules from CO3.0 chondrites tend to be younger than type I chondrule from CO3.0 chondrites [5, 14, 15].

References: [1] Kita N. T. et al. (2000) *GCA, 64*, 3913-3922. [2] Krot A. N. et al. (2009) *GCA, 73*, 4963-4997. [3] Ushikubo T. et al. (2009) *LPS XL*, Abs. #1383. [4] Kita N. T. et al. (2007) Workshop on the Chronology of Meteorites and the Early Solar System, Abs. 92-93. [5] Kurahashi E. et al. (2008) *GCA, 72*, 3865-3882. [6] Hutcheon I. D. et al. (2009) *GCA, 73*, 5080-5099. [7] Sugiura N. and Krot A. N. (2007) *Meteorit. Planet. Sci., 42*, 1183-1195. [8] Huss G. R. et al. (2001) *Meteorit. Planet. Sci., 36*, 975-997. [9] Villeneuve J. et al. (2009) *Science, 325*, 985-988. [10] Rudraswami N. G. et al. (2008) *EPSL, 274*, 93-102. [11] Nagashima K. et al. (2008) *LPS XXXIX*, Abs. #2224. [12] Jacobsen B. et al. (2008) *EPSL, 272*, 353-364. [13] MacPherson G. J. et al. (2009) *Meteorit. Planet. Sci. Suppl.*, 5342. [14] Yurimoto H. and Wasson J. T. (2002)*GCA, 66*, 4355-4363. [15] Kunihiro T. et al. (2004) *GCA, 68*, 2947-2957.

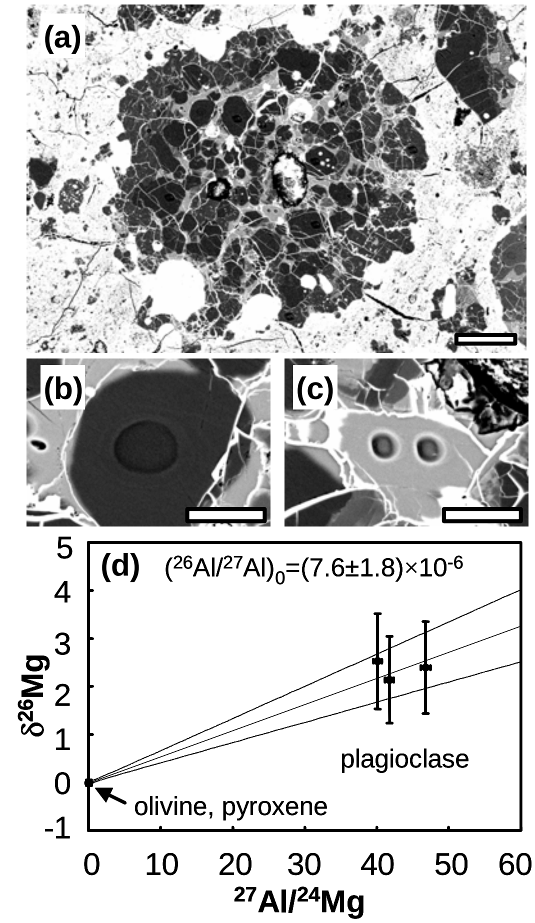

Figure 2. An example of Mg isotope analyses of chondrules. (a) Backscatter electron (BSE) image of a type I chondrule G73. (b, c) BSE image of an ion probe pit with high intensity beam on olivine (b) and with low intensity beam on plagioclase (c). (d) The observed internal isochrone of chondrule G73. Scale bars are 100 μm for (a) and 20 μm for (b) and (c). Errors in (d) are 2 SD.

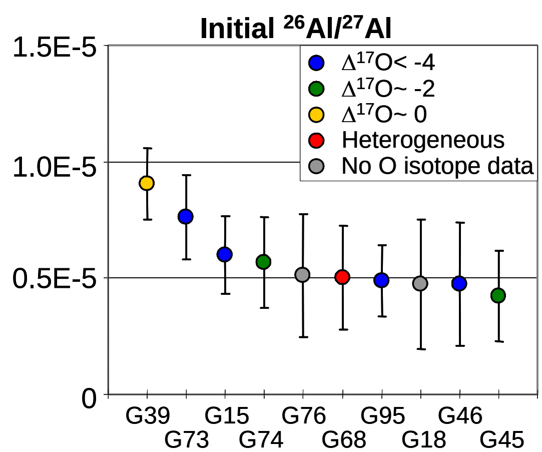

Figure 3. Inferred initial $^{26}Al/^{27}Al$ ratios of chondrules from Acfer 094. Data are arranged according to the order of magnitude of initial $^{26}Al/^{27}Al$ ratios. Errors are 2σ.