AL-MG CHRONOLOGY OF REFRACTORY INCLUSIONS AND CHONDRULES. N. T. Kita[1], T. Ushikubo[1], G. J. MacPherson[2], B. Jacobsen[3], Q-Z. Yin[4], K. Nagashima[5], A. N. Krot[5], E. Kurahashi[6], and S. B. Jacobsen[7], [1]University of Wisconsin-Madison (noriko@geology.wisc.edu), USA. [2]Smithsonian Institution, USA. [3]Lawrence Livermore National Laboratory, USA. [4]University of California Davis, USA. [5]University of Hawai'i at Manoa, USA. [6]University of Münster, Germany. [7]Harvard University, USA.

Introduction: Under the assumption that ^{26}Al was distributed homogeneously in the early Solar System [1,2], the ^{26}Al-^{26}Mg system provides the highest time-resolution among the short-lived radionuclide chronometers due to the short half-life of ^{26}Al, 0.705 Ma [3]. Here, we review the inferred initial ^{26}Al/^{27}Al ratios in Ca, Al-rich inclusions (CAIs), Amoeboid Olivine Aggregates (AOAs), and chondrules based on the recent high-precision Al-Mg isotope measurements using Multi-Collector Secondary Ion Mass Spectrometer (MC SIMS) and Inductively Coupled Plasma Mass Spectrometer (MC ICP-MS). The relative ages among CAIs, AOAs, and chondrules inferred from ^{26}Al-^{26}Mg systems provide important constraints on the models of the protoplanetary disk evolution in the Solar System [e.g., 4,5].

Initial ^{26}Al/^{27}Al ratio of the solar system: In a 1995 review paper, MacPherson et al. [6] showed that the initial ^{26}Al/^{27}Al ratio in most CAIs is ~5×10^{-5}, referred as the "canonical" ratio and considered to represent the initial ^{26}Al/^{27}Al ratio of the solar system. Recently, this ratio was re-evaluated using high-precision ICP-MS measurements of the bulk CAIs from CV3 chondrites [7−10]. All these studies reported well-defined bulk CAI isochrons, indicating that primary condensation of refractory solids in the CV CAI-forming region occurred within a short time (≤ 20 Ka). Although a slightly elevated initial ^{26}Al/^{27}Al ratio (~6×10^{-5}) was once indicated by [7,8], more recent studies reported consistent inferred initial ^{26}Al/^{27}Al ratios of $(5.23\pm0.13)\times10^{-5}$ [9] and $(5.25\pm0.02)\times10^{-5}$ [10]. For internal isochron studies of CAIs from which higher initial ^{26}Al/^{27}Al ratios were indicated [e.g., 11], there are recent efforts by [12] to characterize the internal distribution of Al and Mg within CAIs in order to understand previous data.

Variations of ^{26}Al/^{27}Al ratios among CV CAIs: Many CV CAIs appear to have experienced multiple melting events in the solar nebula. If the last melting was extensive, it could have been recorded by the internal ^{26}Al-^{26}Mg isochrones of an individual inclusion. The parent body alteration experienced by many CV chondrites could result in disturbance of ^{26}Al-^{26}Mg system, as seen in some Allende CAIs [e.g., 13]. As a result, it is important to rely on the ^{26}Al/^{27}Al initial ratios estimated from well-defined ^{26}Al-^{26}Mg isochrons from the least metamorphosed chondrites. Internal ^{26}Al-^{26}Mg isochrons obtained from multiple types of CAIs in the CV chondrites [9, 14−18] show a relatively narrow range of initial ^{26}Al/^{27}Al ratios, ranging from 5.3×10^{-5} to 4.2×10^{-5}, which corresponds to a time difference of ~0.2 Ma. As shown in Fig. 1, there are systematic differences between melted and unmelted CAIs [16], where melted CAIs, including Compact Type A (CTA), Type B, and Type C, are younger (i.e., have lower ^{26}Al/^{27}Al ratios) than the unmelted Fluffy Type A (FTA) that show ^{26}Al/^{27}Al ratios indistinguishable from those of the bulk CV CAIs [9,10]. We note that the inferred ^{26}Al/^{27}Al ratio of the AOA shown in Fig. 1, with the value of $(5.13\pm0.10)\times10^{-5}$ [16], is marginally lower than that of bulk CV CAIs of [10]. An intercept of the ^{26}Al-^{26}Mg isochron ($\delta^{26}Mg_0$) of individual CAIs increases with decreasing initial ^{26}Al/^{27}Al ratios, consistent with the remelting of CAIs having super-chondritic Al/Mg ratios [18].

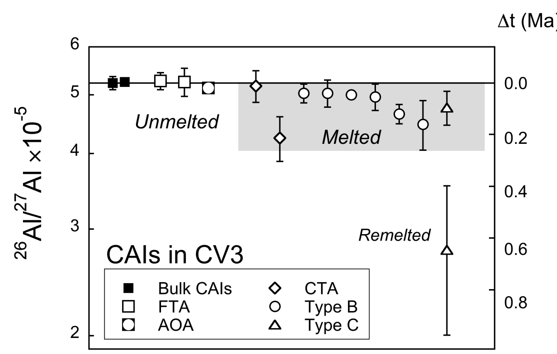

Fig. 1. Variations of ^{26}Al/^{27}Al ratios in several types of CAIs from CV3 chondrites [9−10, 14−17].

It is interesting to note that initial ^{26}Al/^{27}Al ratios of several type B CAIs that were obtained using ICP-MS analyses of mineral separates and high precision MC-SIMS analyses show indistinguishable values at ~5.0×10^{-5}, indicating that there could be major reheating event to produce type B CAIs at ~40 Ka after the time of the initial Al/Mg fractionation in the CAI-forming region.

Evidence for possible heterogeneity of ^{26}Al in the CAI-forming region: There are several types of refractory grains and inclusions with the inferred ^{27}Al/^{27}Al ratios lower than the canonical value. These include FUN CAIs, platy hibonite crystals (PLACs), some corundum-bearing CAIs, and most CAIs from CH carbonaceous chondrites [6, 19, and references therein]. These objects may have formed prior to injection and homogenization of ^{26}Al in the early Solar System [2], but the issue is not resolved yet.

It should be noted that bulk CAI isochrons have been obtained only from CAIs from CV3 chondrites, because their CAIs are large enough to analyze individually. Internal isochron data of CAIs in CR chondrites using SIMS show $^{26}Al/^{27}Al$ ratios indistinguishable from the canonical value [20]. Preliminary SIMS internal isochron data of FTAs from Y-81020 (CO3.0) and Acfer 094 (ungr. C3.0) [21] show slightly lower initial $^{26}Al/^{27}Al$ ratios which are within 10% of the canonical value. They may indicate minor heterogeneity in distribution of ^{26}Al in the CAI-forming region. Alternatively, they may have solidified later. More work in needed to clarify this issue.

Arguments for and against large heterogeneity of ^{26}Al in the protoplanetary disk: The lack of significant heterogeneity of ^{26}Al in the protoplanetary disk is supported by broadly consistent relative ages obtained from ^{26}Al-^{26}Mg, ^{53}Mn-^{53}Cr, and ^{182}Hf-^{182}W ages from multiple meteoritic samples, including CAIs, chondrules and various achondrites [e.g., 22]. High precision ^{26}Al-^{26}Mg analyses of whole-rock chondrites [23] plot along the isochron defined by bulk CV CAIs with initial $\delta^{26}Mg_0$ of −0.040±0.029 ‰ [9], indicating that ^{26}Al heterogeneity in the protoplanetary disk was less than 30%. In contrast, [10] reported that whole-rock CI chondrite data with solar Al/Mg ratios do not plot on the bulk CV CAI isochron, from which they suggested that the protoplanetary disk might have either significant, up to 80%, ^{26}Al heterogeneity, and/or Mg-isotope heterogeneity. However, their bulk CV CAI isochron using both CAIs and AOAs gives initial $\delta^{26}Mg_0$ of −0.016±0.002 ‰ that is slightly elevated from those reported earlier [8,9], which could be due to late formation of AOAs. The whole-rock $\delta^{26}Mg$ values in chondrites and achondrites reported by [10] could be explained by Al/Mg fractionation in the nebula and parent body processes before the complete decay of ^{26}Al without involving heterogeneity of ^{26}Al.

Further studies are required to clarify the level of ^{26}Al heterogeneity in the early solar system that would test the reliability of ^{26}Al chronometer.

Chondrules: The initial $^{26}Al/^{27}Al$ ratios inferred from internal isochrones of chondrules in the least metamorphosed chondrites (type 3.0) are typically in the range of $(0.5-1)\times10^{-5}$, which corresponds to 2−3 Ma after the CAI formation [e.g., 24−28]. Exceptions are CR2 chondrites, in which most chondrules do not show correlated ^{26}Mg excesses and their inferred initial $^{26}Al/^{27}Al$ ratios are less than 3×10^{-6} [29−32]. These data indicate late formation of these chondrule. The time scale of chondrule formation provides our best constraint on the lifetime of the protoplanetary disk from which our solar system formed [1].

According to available data in the literature, the 1SD of the chondrule age distributions in a single meteorite are typically 0.2−0.4 Ma [33 and references therein]. For example, the ^{26}Al ages of type I chondrules in Y-81020 (CO3) and Acfer 094 and those of type II chondrules in Semarkona (LL3) show average values of 2.02±0.23 Ma (1SD, n=14 [27]), 2.25±0.25 Ma (1SD, n=9 [29]), and 2.04±0.28 Ma (1SD, n=4 [25]). Thus, most chondrules in LL3, CO3, and Acfer 094 formed within a narrow time scale, much shorter than a million years. At this level, mixing of solids in the protoplanetary disk due to radial transport would be limited [5] and may preserve the group specific chemical and isotopic characters among chondrules in a single chondrite group [34].

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