High-precision SIMS Al-Mg analysis of FeO-poor chondrules in Asuka 12236 CM2.9 chondrite

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Introduction: Chondrules are melted objects that were produced by transient heating events in the protoplanetary disk. Several mechanisms have been proposed for originating the transient heating events (shock-wave heating, lightning, impact jetting/splashing). Among them, the shock-wave heating and impact jetting models are the most favorable candidates [1, 2]. If correct, chondrule formation events require the existence of proto-Jupiter, planetary embryos, and/or large planetesimals, suggesting that chondrules might have formed as a consequence of planetary growth. Therefore, determining the timing and location of chondrule formation events provides key constraints on the spatial-temporal evolution of planetary bodies in our Solar System.

Fukuda et al. [3] suggested that the discrete chondrule-forming events in different disk regions reflect a time difference in the growth of planetesimals within the first 4 million years (Ma) in the protoplanetary disk based on the observation that chondrule formation in the outer disk was delayed relative to that in the inner disk. To further demonstrate the possible time difference in chondrule formation between the inner and outer disk, we conducted high-precision Al-Mg isotope analyses of chondrules in one of the most pristine CM chondrites Asuka 12236 (A 12236) [4].

Sample and Methods: Seven type I (Mg# >90; where Mg# = Mg/[Mg + Fe] molar%) chondrules in A 12236 containing anorthitic plagioclase were picked for Al-Mg isotope analyses. One of the chondrules studied appears to have altered regions in their mesostases. We carefully avoided these areas for Al-Mg isotope analyses and only measured clean anorthite grains. The Al-Mg isotope systematics of 2 out of the 7 chondrules have been investigated for plagioclase grains larger than 10 µm [3]. In addition to these data, plagioclase grains smaller than 10 µm in the 2 chondrules were analyzed here. The determined initial ratios, $(^{26}Al/^{27}Al)_0$, of the 2 chondrules are deduced from the combined data obtained in this study and [3]. Major and minor element abundances and oxygen three-isotope ratios of chondrule minerals (olivine, pyroxene, plagioclase) in the 7 chondrules have been reported in the NIPR meeting in 2020 [5]. Al-Mg isotope analyses of olivine, pyroxene, and plagioclase were performed with the WiscSIMS Cameca IMS 1280 equipped with the radio-frequency ion source at UW-Madison. For olivine and pyroxene, a 2.6 nA $^{16}O^-$ primary ion beam focused to ~9 µm in diameter was used. The three Mg isotope and $^{27}Al^+$ signals were detected simultaneously on the multi-collection Faraday Cups (MCFC) [3, 6, 7]. Plagioclase grains are typically smaller than ~10 µm and, therefore, analyzed using a ~6 µm diameter $^{16}O^-$ primary ion beam with an intensity of 0.5 nA. Mg isotope signals were detected by one FC for $^{24}Mg^+$ and two electron multipliers for $^{25}Mg^+$ and $^{26}Mg^+$. The $^{27}Al^+$ signal was detected by FC. Secondary ion optics and data reduction procedures are similar to those described in [3, 6, 7].

Results: The $\delta^{26}Mg^*$ values in plagioclase range from 0.1 ± 0.5 ‰ to 2.9 ± 0.6 ‰ (2σ), with corresponding $^{27}Al/^{24}Mg$ ratios ranging from 23 to 54. Olivine and pyroxene exhibit a limited variation in $\delta^{26}Mg^*$ values ranging from −0.11 ± 0.11 ‰ to 0.06 ± 0.10 ‰ (2σ) with $^{27}Al/^{24}Mg$ ratios ≤ 0.04. The inferred initial $^{26}Al/^{27}Al$ ratios, $(^{26}Al/^{27}Al)_0$, of the 7 chondrules, range from $(3.2 \pm 1.5) \times 10^{-6}$ to $(6.6 \pm 0.9) \times 10^{-6}$ (95% confidence intervals). Assuming a homogeneous distribution of ^{26}Al in the Solar protoplanetary disk [e.g., 8, 9] with an initial $^{26}Al/^{27}Al$ ratio of 5.25×10^{-5}, inferred from bulk Al-Mg isotope measurements of Ca-Al-rich inclusions (CAIs) in CV chondrites [10], the observed $(^{26}Al/^{27}Al)_0$ values of the 7 chondrules correspond to formation ages ranging from $2.1\ ^{+0.2}/_{-0.1}$ Ma to $2.8\ ^{+0.7}/_{-0.4}$ Ma after CAI formation.

Discussion: So far 10 chondrules from A 12236 have been analyzed for determining Al-Mg ages [3 and this study]. Except for chondrule A75 with heterogeneous oxygen isotope ratios (−3.8‰ < $\Delta^{17}O$ < −0.5‰) [3], the remaining nine exhibit Al-Mg ages ranging from $2.1\ ^{+0.2}/_{-0.1}$ Ma to $2.8\ ^{+0.7}/_{-0.4}$ Ma after CAIs. The Al-Mg ages of CM chondrule formation is well-overlapped with those of chondrules in the other carbonaceous chondrites such as CV, CO, and Acfer 094 [3, 11-13] and systematically younger than chondrules in ordinary chondrites (OCs) (~1.8–2.2 Ma after CAIs [6, 7]) that formed in the inner regions of the protoplanetary disk [14]. The oxygen isotope ratios (mean $\Delta^{17}O$ values) of the 9 chondrules from A 12236 are typical of the CM chondrules (−4.3‰ to −5.5‰ [3, 5]), which were likely formed in a moderately high dust-enriched region (~50–100 × Solar [15, 16]) based on the oxygen isotope mass balance model proposed by [17]. Notably, the oxygen isotope ratios of the CM chondrules studied are also indistinguishable from those in the other major carbonaceous chondrite groups such as CV and

COs [e.g., 3, 18, 19, 20], indicating that the 7 CM chondrules formed in the outer region of the protoplanetary disk. Thus, our new Al-Mg data supports the hypothesis that the chondrule formation in the outer Solar System postdates those in the inner Solar System, which would be related to discrete planetesimal formation in different disk regions [3].

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References:

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