A TEMPORAL SHIFT OF CHONDRULE GENERATION FROM THE INNER TO OUTER SOLAR SYSTEM.

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Introduction: Deciphering the spatial and temporal evolution of chondrules allows for a better understanding of how asteroidal seeds formed, migrated, and eventually accreted into parent asteroids. Chondrule formation appears to have occurred contemporaneously in the inner and outer Solar System (~0-4 Myr after CAIs) [e.g., 1,2]. However, the protracted chondrule formation, especially for the outer disk, would not be consistent with the distinct chondrule properties among each chondrite group [e.g., 3]. The majority of carbonaceous chondrite (CC) parent bodies accreted >3 Myr after CAIs [e.g., 4]. Thus, the later accretion of asteroids in the outer disk indicates a time interval of up to ~3 Myr between primary chondrule formation and their subsequent accretion into the CC parent asteroids. This time interval would not have allowed for the retainment of the distinct chondrule properties among each chondrite group since mixing timescales within the asteroidal belt could have been <<1 Myr [e.g., 5]. To better constrain the timescale of chondrule formation in the outer Solar System, we obtained new high precision Al-Mg ages as well as oxygen isotope ratios of chondrules from the primitive CM and CO chondrites, Asuka (A) 12236 (CM2.9), Dominion Range (DOM) 08006 (CO3.00-3.01), and Yamato (Y)-81020 (CO3.05). This is the first report of Al-Mg ages of CM chondrules.

Samples and Methods: We studied 15 FeO-poor chondrules (Mg# > 98; Mg# = [Mg]/[Mg + Fe] in molar %). Al-Mg and oxygen isotope analyses of chondrule minerals were performed with the WiscSIMS Cameca IMS 1280. Analytical conditions are similar to those described in [6] for Al-Mg analyses and [7] for oxygen isotope analyses. We note Al-Mg analyses of plagioclase were conducted using 10 µm diameter (O_2^-, 2 nA) using multi-collector Faraday cups. Oxygen isotope ratios of the A 12236 and Y-81020 chondrules were reported in [7] and [8], respectively. Preliminary Al-Mg results of the Y-81020 chondrules were reported in [9].

Results and Discussion: Fourteen out of the 15 chondrules exhibit a restricted range of inferred initial ^{26}Al/^{27}Al ratios, (^{26}Al/^{27}Al)$_0$ = (3.6-6.0)×10^{-6}, corresponding to Al-Mg ages ranging from ~2.2 to ~2.8 Myr after CAIs. Their mean Δ^{17}O values range from −6‰ to −4‰, consistent with those from the majority of CCs [10], suggesting they formed in the outer disk. Notably, the Al-Mg ages of the CM and CO chondrules as well as other pristine CCs, such as Kaba (CV3.1) and Acfer 094 (Ung. C3.00), are systematically younger than those of the majority of unequilibrated ordinary chondrite (UOC) chondrules that formed in the inner disk [6,11-14]. The majority of CR chondrules formed later than 2.8 Myr after CAIs [e.g., 15]. CR chondrites/chondrules exhibit distinct isotopic characteristics compared to other CCs, indicating that CR chondrules originated outside the formation regions of chondrules from CM, CO, and CV chondrites [e.g., 16]. If correct, our results provide evidence for delayed chondrule formation with increasing heliocentric distance. The discrete chondrule-forming events in different disk regions would reflect a time difference in growth and orbital evolution of planetesimals within the first 4 Myr of the Solar System.

One chondrule, A75 from A 12236, has an exceptionally high (^{26}Al/^{27}Al)$_0$ = (8.0±0.7)×10^{-6}, meaning that this chondrule formed almost contemporaneously with UOC chondrules. This chondrule exhibits ^{16}O-depleted characteristics (−4‰ < Δ^{17}O < 0‰), suggesting that this chondrule did not form in the disk regions where the majority of CC chondrules formed [7]. This chondrule might have formed between OC and CC chondrule formation regions and was then transported to the accretion region of the CM parent body in more than 1 Myr.

References: [1] Kurahashi E. et al. (2008) *Geochimica et Cosmochimica Acta* 72: 3865-3882. [2] Bollard J. et al. (2017) *Science Advances* 3: e1700407. [3] Hezel D. C. and Palme H. (2010) *Earth and Planetary Science Letters* 294: 85-93. [4] Sugiura N. and Fujiya W. (2014) *Meteoritics & Planetary Science* 49: 772-787. [5] Cuzzi J. et al. (2010) *Icarus* 208: 518-538. [6] Siron et al. (2021a) *Geochimica et Cosmochimica Acta* 293: 103-126. [7] Fukuda K. et al. (2020) *The 11th symposium on Polar Science*, Abstract #100. [8] Tenner T. J. et al. (2013) *Geochimica et Cosmochimica Acta* 102: 226-245. [9] Kita N. T. et al. (2020) *Goldschmidt* Abstract #1329. [10] Tenner T. J. et al. (2018) In *Chondrules: Records of Protoplanetary Disk Processes*, 196-246. [11] Siron et al. (2021b) *LPS LII*, Abstract #1639. [12] Nagashima K. et al. (2017) *Geochimica et Cosmochimica Acta* 201: 303-319. [13] Ushikubo T. et al. (2013) *Geochimica et Cosmochimica Acta* 109: 280-295. [14] Hertwig A. T. et al. (2019) *Geochimica et Cosmochimica Acta* 253: 111-126. [15] Nagashima K. et al. (2014) *Geochemical Journal* 48: 561-570. [16] Olsen M. et al. (2016) *Geochimica et Cosmochimica Acta* 191: 118-138.