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Summary: Evidence from short-lived (^{26}Al-^{26}Mg, ^{53}Mn-^{53}Cr) and long-lived (^{207}Pb-^{206}Pb) isotope systematics, oxygen isotopes, nuclear isotopic effects, mineralogy and petrography all suggest that Ca,Al-rich inclusions (CAIs) and amoeboid olivine aggregates (AOAs) were the first solids to form in the solar nebula, possibly within a period of <0.1-0.3 Myr, when the Sun was accreting rapidly as a class 0 or I protostar. CAIs and AOAs formed during multiple episodes either throughout the inner solar nebula (up to 4 AU) or in a localized nebular region (<0.1 AU) and were subsequently dispersed throughout the nebula. Most chondrules and meteorite matrix materials formed throughout the inner solar nebula 1-3 Myr after refractory inclusions, when the Sun was accreting more slowly. The majority of chondrules within each individual chondrite group may have formed over a much shorter period (<0.5-1 Myr). CAIs and AOAs were probably present in or near the chondrule-forming regions at the time of chondrule formation, but were largely unaffected by chondrule melting events. Chondrules and metal grains in CB chondrites formed during a single stage event ~4 Myr after CAIs, possibly from a vapor-melt plume generated by a collision between planetary embryos.

Chondritic components and their origin: The major chondritic components are CAIs, AOAs, chondrules, metal, and fine-grained matrix. CAIs are 0.1-20 mm-sized objects composed mostly of oxides and silicates of Ca, Al, Ti and Mg. AOAs are aggregates of mostly forsterite and Fe,Ni-metal, with small enclosed spinel-diopside-anorthite CAIs. Chondrules are igneous objects, 0.01-10 mm in size, composed largely of Fe,Mg-olivine and low-Ca Fe,Mg-pyroxene, Fe,Ni-metal and glassy mesostasis. Matrices of primitive (unmetamorphosed) chondrites consist largely of µm–sub-µm grains of crystalline Mg-olivine and low-Ca Mg-pyroxene, Fe,Ni-metal, sulfides, oxides and amorphous Fe,Mg-silicates. Evidence from mineralogical, chemical and isotopic studies suggest that CAIs and AOAs formed in an ^{16}O-rich ($\Delta^{17}O \leq -20$‰) but reducing environment of near-solar composition, at total pressure $\leq 10^{-4}$ bar and ambient temperature at or above condensation temperature of forsterite (~1300 K), possibly very near the protosun. In contrast, most chondrules and matrices formed in an ^{16}O-depleted ($\Delta^{17}O \geq -10$‰) nebular gas, under variable but generally more oxidizing conditions and lower ambient temperatures (<1000 K) than did CAIs and AOAs, and in regions with sufficiently high dust/gas ratios to stabilize silicate melts for perhaps hours, which can also satisfy the observed lack of mass-dependent isotopic fractionation in the vast majority of chondrules [1-3]. The apparent complementarity of chemical compositions of primitive chondrite chondrules and matrices [4], their similar oxygen isotopic compositions [5], and the high abundance of crystalline silicates in primitive chondrite matrices suggest that significant fraction of matrix materials was thermally processed during transient heating events that formed host chondrite chondrules [1], which is inconsistent with X-wind model of chondrule formation [6-8]

Absolute chronology of CAI and chondrule formation: ^{207}Pb-^{206}Pb isotopic ages of coarse-grained CAIs in CV chondrites Efremovka and Allende are 4567.11±0.16 and 4567.7±0.9 Myr, respectively [9-11], whereas ^{207}Pb-^{206}Pb ages of chondrules from CV, CR and CB carbonaceous chondrites are 4565.7±0.4 [12], 4564.7±0.6 [10] and 4562.7±0.5 Myr [13], respectively. These data indicate that chondrule formation lasted for several Myr, but the majority of chondrules within an individual chondrite group may have formed within ≤1 Myr. The resolved age difference (2±1 Myr) between CAIs and chondrules from Allende contradicts an X-wind hypothesis of contemporaneous formation of CAIs and chondrules in a single chondrite group [6-8].

Relative chronology of CAI and chondrule formation: Mineralogical and isotopic evidence indicates that, in each of the known chondrite groups, CAI formation predated chondrule formation [14]: (*i*) relict CAIs occur inside chondrules, and some CAIs are enclosed by chondrule-like igneous rims [14, 15], (*ii*) oxygen isotopic evidence indicates remelting of some CAIs in an ^{16}O-depleted nebular gas [16], and (*iii*) volatility fractionated, group II REE patterns in some chondrules indicate presence of CAIs among their precursors [17]. The similarities in mineralogy and isotopic compositions of CAIs inside and outside chondrules within an individual chondrite group suggest that CAIs were present in or near chondrule-forming regions at the time of chondrule formation, but were largely unaffected by chondrule melting events [18]. There is no unambiguous evidence that chondrules experienced re-melting in the CAI-forming region [19].

^{26}Al-^{26}Mg systematics: The use of the short-lived radionuclide ^{26}Al ($t_{1/2}$ = 0.73 Myr) as a high-resolution chronometer [specifically, inferred initial ^{26}Al/^{27}Al ratios (^{26}Al/^{27}Al)$_0$] for dating CAI and chondrule formation requires the assumption of ^{26}Al uniform distribution throughout the inner solar nebula, where CAIs and chondrules probably formed [20]. Cross-calibration of ^{26}Al-^{26}Mg and ^{207}Pb-^{206}Pb chronometers [21-23], and high-precision Mg isotope measurements of bulk chondrites, Earth and Mars [24], have validated the assumption and thus confirmed the chronological significance of ^{26}Al-^{26}Mg systematics.

Most CAIs, and few AOAs analyzed so far, define (^{26}Al/^{27}Al)$_0$ of ~5×10^{-5}, referred to as the "canonical" value [20, 25]. The canonical ratio has been recently revised upwards to a "supra-canonical" value of $(5.85\text{-}7)\times10^{-5}$ [24, 26-30]. Note the importance of Mg isotopic fractionation laws (exponential, equilibrium, or experimentally derived) in correction of Mg isotope data and in comparing isochrons for mass-fractionated CAIs [31]. High-precision Mg isotope measurements of bulk igneous Allende CAIs and their mineral separates using MC-ICPMS define (^{26}Al/^{27}Al)$_0$ of $(5.12\pm0.18)\times10^{-5}$ [32], which is inconsistent with $(5.85\pm0.05)\times10^{-5}$ value reported by [24] using the same analytical technique. Although this apparent discrepancy still needs to be resolved, both data sets suggest a very short (<20-30 Kyr) time difference between the formation of precursors of the igneous CV CAIs and their crystallization ages. To constrain the total duration of CAI formation, high precision measurements of internal Al-Mg isochrons in CAIs from primitive carbonaceous chondrites (e.g., CR2, CO3.0, Acfer 094, Adelaide) are required.

High-precision Al-Mg isotope measurements for chondrules from primitive chondrites are limited [33-40]. In CO3.0 chondrite Y-81020, the (^{26}Al/^{27}Al)$_0$ ranges from $(0.24\pm0.17)\times10^{-5}$ to $(1.4\pm0.3)\times10^{-5}$ [mean = $(8\pm4)\times10^{-6}$], which corresponds to an age difference of 1.3-3.2 Myr after CAIs with the canonical ^{26}Al/^{27}Al ratio [36, 37]. No systematic differences were found between the (^{26}Al/^{27}Al)$_0$ in chondrules from Y-81020 and those in chondrules from Semarkona (LL3.0) and Bishunpur (LL3.1) [(^{26}Al/^{27}Al)$_0$ ranges from $(0.46\pm0.21)\times10^{-5}$ to $(2.28\pm0.73)\times10^{-5}$; mean = $(1\pm0.5)\times10^{-5}$] [33-39]. In contrast, most chondrules in CR2 chondrites have (^{26}Al/^{27}Al)$_I$ <0.3×10^{-5} [40], consistent with their young ^{207}Pb-

^{206}Pb ages [10]. The young crystallization ages of primitive chondrite chondrules inferred from internal Al-Mg isochrons are in apparent conflict with the whole-chondrule Al-Mg isochrons [(^{26}Al/^{27}Al)$_0$ ~(3-5)×10^{-5}] inferred from bulk Mg-isotopic compositions of CV chondrules [26]. Note, however, that the whole-chondrule Al-Mg isochrons correspond to the formation time of chondrule *precursors*, not chondrule crystallization ages; the latter can be inferred only from internal Al-Mg isochrons. According to an X-wind model, chondrules formed in the disk and were well protected from irradiation by energetic particles. As a result, large excesses of ^{26}Mg reported in bulk CV chondrules are [26] in conflict with the X-wind model and its local irradiation origin for ^{26}Al [6-8].

^{53}Mn-^{53}Cr systematics: ^{53}Mn-^{53}Cr systematics of chondrules from Chainpur (LL3.4) define an initial ^{53}Mn/^{55}Mn of (5.1±1.6)×10^{-6} [41], which is similar to the value for Semarkona (LL3.0) chondrules (5.8±1.9)×10^{-6} [38]. Relative to the Solar System's initial ^{53}Mn/^{55}Mn of (8.5±1.5)×10^{-6} obtained from bulk carbonaceous chondrites [42, 43], chondrules in ordinary chondrites are 2.73 Ma younger than CV CAIs, which is in a good agreement with the ^{26}Al-^{26}Mg systematics of ordinary chondrite chondrules [38].

^{60}Fe-^{60}Ni systematics: Although ^{60}Fe ($t_{1/2}$ = 1.49 Myr) can potentially be a high-resolution early Solar System chronometer, its chronological implication for CAI and chondrule formation is still limited and controversial. The presence of ^{60}Ni excess due to decay of ^{60}Fe has been reported in chondrule silicates and sulfides, but the initial abundance of ^{60}Fe remains poorly constrained [44-49]. The initial ^{60}Fe/^{56}Fe ratio in Fe,Mg-silicates from Semarkona and Bishunpur chondrules ranges from (2.2±1.0)×10^{-7} to (3.7±1.9)×10^{-7} [46]. By applying the time difference of 1.5-2.0 Myr between formation of CAIs and chondrules, a Solar System initial ^{60}Fe/^{56}Fe of (5-10)×10^{-7} is estimated [46]. This estimate may be invalid, if ^{60}Fe and ^{26}Al were decoupled [47]. Note that although ^{60}Ni excesses have been reported in CAIs [48], these excesses are probably due to nucleosynthetic anomalies rather than decay of ^{60}Fe.

Chronology and O-isotopic compositions of chondritic components: If O-isotopic composition of the Sun (yet to be measured on Genesis samples) is similar to that of CAIs and AOAs from primitive chondrites (Δ^{17}O ≤ –20‰) [50, 51], then the differences in O-isotopic compositions between CAIs+AOAs and chondrules+matrices (Δ^{17}O ≥ –10‰) can be interpreted chronologically [52]. Note that the origin of ^{16}O-rich reservoir in the early Solar System and O-isotopic composition of the Sun remains controversial [53]. In addition, the evidence for coexistence of ^{16}O-rich and ^{16}O-poor gaseous reservoirs during early crystallization of igneous CAIs in CV chondrites [54, 55] and the lack of clear correlation between a degree of ^{16}O-enrichment in chondrules and their crystallization ages [56] may reduce chronological significance of oxygen isotopes.

Chronology of CB chondrites: Chondrules and metal grains in CB chondrites are mineralogically, chemically and isotopically unique. The CB chondrules coexist with Fe,Ni-metal condensates, have exclusively Mg-rich compositions and non-porphyritic (cryptocrystalline or skeletal) textures, flat REE patterns, similar O-isotopic compositions and young ^{207}Pb-^{206}Pb ages, and show no evidence for remelting [13]. Chondrules and metal grains show mass-dependent fractionation effects in Mg, Fe and Ni [57, 58]. It is suggested that chondrules and metal grains in CBs formed during a single-stage event, possibly from a gas-melt plume generated by a collision between planetary embryos; rare ^{16}O-depleted CAIs in CBs were remelted during this event [13]. If this is the case, chondrules and metal grains in CBs can potentially allow to link several relative chronometers to the absolute time scale.

Chronology of ^{26}Al-poor CAIs: A rare subset of CAIs (so-called FUN CAIs and some platy hibonite grains (PLACs) and corundum-rich CAIs) contain relatively large nucleosynthetic isotope anomalies, and had little or no ^{26}Al at the time of their formation. It has been suggested that such objects formed relatively early, prior to injection and homogenization of ^{26}Al in the Solar System [59, 60]. Measurements of ^{207}Pb-^{206}Pb ages of such CAIs are required to test this hypothesis. The common presence in CH chondrites of very refractory (grossite- and hibonite-rich), ^{16}O-rich and ^{26}Al-poor [(^{26}Al/^{27}Al)$_I$) < 10^{-6}] CAIs, which typically show no nuclear isotopic anomalies or mass-dependent fractionation effects, is intriguing [61-63]. These CAIs may have formed either very early, like is assumed for FUN CAIs and PLACs, or very late, after decay of ^{26}Al.

Presence of asteroidal material among chondrule precursors? If there is 1-2 Myr gap between CAIs and chondrules, and accretion and differentiation of planetesimals predated or overlapped with chondrule formation [63], fragments of these early differentiated bodies might be expected within chondrites or even among chondrule precursors. It has been recently shown that coarse-grained lithic clasts of forsteritic olivine with granoblastic textures inside magnesian porphyritic chondrules from CV chondrites are relict [65, 66]. Formation of the granoblastic textures requires sintering and prolonged, high-temperature (>1000°C) annealing [67] – conditions which are not expected in the solar nebula during chondrule formation, but could have been achieved on parent bodies. If these objects are indeed fragments of thermally processed planetesimals that were present among chondrule precursors, they will place important constraints on the early Solar System chronology. More work is required to establish this possibility, including whether they have trace element fractionation patterns indicative of igneous differentiation as opposed to volatility control.

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