
Summary: Evidence from short-lived (26Al-26Mg, 53Mn-55Cr) and long-lived (207Pb-206Pb) isotopic systematics, oxygen isotopes, nuclear isotopic effects, mineralogy and petrography all suggest that Ca-Al-rich inclusions (CAIs) and amboeleoid 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-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 and glassy mesostasis. Matrices of primitive (unmetamorphosed) chondrites consist largely of μm –sub-μm grains of crystalline Mg-olivine and low-Ca Fe,Mg-pyroxene, Fe,Ni-metal and glassy mesostasis. Evidence from chemical and isotopic studies suggest that CAIs and AOAs formed in an 16O-rich (18O/16O ≈ 1%0) but reducing 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 chondritic 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 a X-wind model of chondrule formation [6-8].

Absolute chronology of CAI and chondrule formation: 207Pb-206Pb 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 207Pb-206Pb ages of chondrules from CV, CR and CB carbonaceous chondrites are 4565.7±0.4 [12], 4564.7±0.6 [10] and 4562.7±0.6 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.

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 16O-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].

26Al-26Mg systematics: The use of short-lived radionuclide 26Al (τ1/2 = 0.73 Myr) as a high-resolution chronometer [specifically, inferred initial 26Al/27Al ratios ([26Al/27Al]) for dating CAI and chondrule formation requires the assumption of 26Al uniform distribution throughout the igneous solar nebula, which CAIs and chondrules were likely formed [20]. Cross-calibration of 26Al-26Mg and 207Pb-206Pb systematics [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 26Al-26Mg systematics.

Most CAIs, and few AOAs analyzed so far, define ([26Al/27Al]) 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±0.5)×10^-5 [26, 27]. 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 meteorites and their mineral separates using MC-ICPMS define ([26Al/27Al]) of (5.1±0.18)×10^-5 [32], which is consistent with (5.85±0.5)×10^-5 value reported [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 isotrons 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 ([26Al/27Al]) ranges from (0.24±0.17)×10^-5 to (1.4±0.3)×10^-5 [mean = (8±4)×10^-6], which corresponds to an age difference of 1.3-3.2 Myr after CAIs with the canonical 26Al/27Al ratio [36, 37]. No systematic differences were found between the ([26Al/27Al]) in chondrules from Y-81020 and those in chondrules from Semarkona (LL3.0) and Bishunpur (LL3.1) ([26Al/27Al]) ranges from (0.4±0.2)×10^-5 to (2.9±0.2)×10^-5 [39, 33] and CR2 chondrites have ([26Al/27Al]) <0.3×10^-5 [40], consistent with their young 207Pb-
The young crystallization ages of primitive chondrule chondrules inferred from internal Al-Mg isochrons are in apparent conflict with the whole-chondrule Al-Mg isochrons ([11Al/27Al] ~ 3.5×10^-6) 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 protected from irradiation by energetic particles. As a result, large excesses of 60Fe reported in bulk CV chondrules are in conflict with the X-wind model and its local irradiation origin for 60Al [6-8].

**Mn-53Cr systematics:** Although Mn-53Cr systematics of chondrules from Chainpur (LL3.4) define an initial Mn53/Mn55 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 Mn53/Mn55 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 “AI-2Al” systematics of ordinary chondrite chondrules [38].

**Ni systematics:** Although 60Fe/(5-10)×10^-7 is estimated [46]. This estimate may be invalid, if 60Fe and 26Al were decoupled [47]. Note that although Ni excesses have been reported in CAIs [48], these excesses are probably due to nucleosynthetic anomalies rather than decay of 60Fe.

**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-isotope compositions and young 207Pb/206Pb 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 18O-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 Al-poor CAIs:** A rare subset of CAIs (so-called FUN CAIs and some platy hibonite grains (PLACs) and coronundum-rich CAIs) contain relatively large nucleosynthetic isotope anomalies, and had little or no 26Al at the time of their formation. It has been suggested that such objects formed relatively early, prior to injection and homogenization of 26Al in the Solar System [59, 60]. Measurements of 207Pb-206Pb ages of such CAIs are required to test this hypothesis. The common presence in CH chondrites of very refractory (gossite- and hibonite-rich), O-rich and Al-poor ([26Al/26Mg] < 10^-7) 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 26Al.

**Presence of asteroidal material among chondrule precursors:** If there is 1-2 Myr gap between CAIs and chondrules, and accretion and differentiation of planetesimals is a very short and prolonged, high-energy process (3-5×10^6 yr) [64], 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.