

# CA-, AL-RICH INCLUSIONS AND AMOEBOID OLIVINE AGGREGATES: WHAT WE KNOW AND DON'T KNOW ABOUT THEIR ORIGIN.

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**General Observations**—Calcium-aluminum-rich inclusions (CAIs) in chondritic meteorites are <100  $\mu\text{m}$  to >2 cm-sized objects consisting mostly of oxides and silicates of calcium, aluminum, titanium, and magnesium [1–4]. The dominant primary minerals are spinel ( $\text{MgAl}_2\text{O}_4$ ), Al-Ti<sup>3+</sup>-rich calcic pyroxene ( $\text{CaMgSi}_2\text{O}_6$ - $\text{CaAl}_2\text{SiO}_6$ - $\text{CaTi}^{3+}\text{AlSiO}_6$ - $\text{CaTi}^{4+}\text{Al}_2\text{O}_6$ ), melilite solid solution ( $\text{Ca}_2\text{Mg}_x\text{Al}_{2-2x}\text{Si}_{1+x}\text{O}_7$ ), hibonite ( $\text{CaMgTiAl}_{12-2x}\text{O}_{19}$ ), perovskite ( $\text{CaTiO}_3$ ), and anorthite ( $\text{CaAl}_2\text{Si}_2\text{O}_8$ ) (see [5] for detailed mineral chemistry and a complete list of accessories). CAIs exhibit a great diversity of chemical, mineralogical, and textural properties, collectively indicating a wide range of evolutionary histories. Amoeboid Olivine Aggregates (AOAs) are irregularly-shaped objects consisting mostly of olivine but commonly containing within them small CAI nodules whose main constituents are spinel, pyroxene, and anorthite. High-precision U-Pb age measurements indicate that CAIs have ages of 4.57 Ga [7]; CAIs also have the lowest measured initial <sup>87</sup>Sr/<sup>86</sup>Sr ratios of any solar system material [8, 9]. Most CAIs have remarkable isotopic properties: many contain the decay products of short-lived radionuclides, including <sup>26</sup>Al, <sup>41</sup>Ca, <sup>10</sup>Be, and <sup>53</sup>Mn [10], that existed at the time of solar system formation; most CAIs and also AOAs show non-mass dependent enrichment (up to several percent relative to terrestrial standards) in <sup>16</sup>O over both <sup>17</sup>O and <sup>18</sup>O [e.g. 11]; and, many CAIs show small degrees of mass-dependent isotopic fractionation in elements such as silicon and magnesium. A peculiar but important subset of CAIs, called FUN inclusions, contain large nuclear (nonradiogenic) isotope anomalies (e.g. in <sup>50</sup>Ti) of nucleosynthetic origin coupled with large degrees of mass-dependent isotopic fractionation and near absence of former <sup>26</sup>Al. CAIs are sorted with respect to both size and type among the various chondrite types [4]. For example: CV3 chondrites contain by far the largest CAIs (1–2 cm), have a virtual monopoly on the prominent Type B [1] CAIs, and most CAIs show the effects of late-stage secondary mineralization that commonly included the introduction of alkalis and oxidized iron; CM chondrites contain small (<1 mm) CAIs that are hibonite-rich and nearly devoid of melilite, a phase common in CAIs in all other (except CI) chondrite types; CAIs in CR and CH chondrites commonly contain grossite ( $\text{CaAl}_4\text{O}_7$ ), a phase that is extremely rare in all other chondrite types.

**Reasonable Inferences**—The U-Pb [7] and initial <sup>87</sup>Sr/<sup>86</sup>Sr [8, 9] studies indicate that CAIs are the oldest objects known to have formed in the solar system. The demonstrated initial presence of short-lived radionuclides such as <sup>26</sup>Al and <sup>41</sup>Ca requires CAI formation within ~1 My of the nucleosynthesis of those isotopes.

The major and trace element bulk chemical compositions of CAIs are unequivocally the result of one or more high temperature volatility-controlled processes, including gas condensation and melt evaporation, and these processes almost certainly occurred in a nebular setting. The ubiquitous presence of trivalent titanium in primary pyroxenes indicates that the CAIs formed in a highly reducing environment, consistent with a hot, hydrogen-rich gas. To a first approximation, the bulk chemistry of CAIs agrees reasonably well with the predictions of equilibrium thermodynamic condensation calculations for a hot gas of solar composition [e.g., 12], although many silicate-rich CAIs are observed to be systematically depleted in Mg and Si relative to the calculations [13]. Nevertheless, the bulk compositions of all CAI varieties taken together with those of AOAs and Al-rich chondrules define a combined trend in bulk composition space that roughly parallels that predicted by equilibrium condensation of a solar gas. Refractory trace element patterns in CAIs and AOAs are in some cases unfractionated with respect to cosmic (bulk solar) compositions and thus cannot be the result of “planetary” processes such as igneous differentiation or metal-silicate separation. For those CAIs and AOAs in which the trace elements are fractionated, the patterns equally can only be the result of volatility-controlled processes, either fractional condensation or melt distillation. It is well established from observational and experimental evidence that many CAIs were melted, some more than once. It is equally well established that some other CAIs were not melted, and in some cases (e.g., the various kinds of melilite-rich Type As) it can fairly be concluded that unmelted ones represent the precursors to some of the melted ones. For others, most notably the prominent Type Bs (all of which are igneous), the precursors have not been identified. AOAs are similar to some Al-rich chondrules in composition, but in general are more olivine-rich and silica-poor. Many CAIs were melted repeatedly (the heat source for which remains uncertain), apparently with significant time intervals and secondary alteration between melting events. Inferences based on evidence for <sup>26</sup>Al suggest that evolutionary time scales (melting, alteration, remelting) for individual CAIs in the nebula commonly were as long as 1–2 My [e.g. 14]. Recent measurements of oxygen and beryllium-boron isotopes have significantly changed our understanding of CAI formation. The canonical model for oxygen isotopes in CAIs was that the <sup>16</sup>O-rich signature derived from incompletely evaporated presolar grains, that were incorporated into CAIs, which later equilibrated to varying degrees with <sup>16</sup>O-poor nebular gas. The discovery that bona fide presolar grains are

almost never  $^{16}\text{O}$ -rich, together with the finding that likely nebular condensate materials (AOAs, and CAIs having trace element fractionation patterns that can only be the result of condensation) are  $^{16}\text{O}$ -rich, suggest that it was the nebular gas and not the residual solids that were  $^{16}\text{O}$ -rich. The CAI precursors thus condensed from  $^{16}\text{O}$ -rich gas. The source of the  $^{16}\text{O}$ -rich signature is no longer thought to be presolar grains but, instead, the result of mass-independent chemical processes in the solar nebula [15, 16]; the observation that all CAIs and AOA's originally had virtually indistinguishable oxygen isotopic signatures led to the idea that all of these objects formed in a single and restricted nebular environment and were later distributed to the various chondrite-accreting regions. This idea was supported by the discovery [17] that CAIs contained the short-lived radionuclide  $^{10}\text{Be}$  at the time of their formation, because that isotope is generally thought not to be formed in stars but rather was likely formed locally in the solar nebula, *near the protosun*, as a result of particle bombardment [17] (although production in the interstellar medium is also a possibility [18]). Thus CAIs may all have formed near the sun.

*Unanswered Questions and Problems*—The data noted above have been used to support a model similar to that of [19] in which high temperature objects such as CAIs formed near the protosun and then were entrained in magnetically-driven bipolar outflow (“X-wind”) outwards from the sun. According to this model, much of the outflow was ejected into interstellar space, but some fell material back onto the nebular disk at large distances from the sun and there was available to be accreted into growing solid bodies. However, some observations cannot be obviously reconciled with such a model. (1) Nuclear anomalies in FUN inclusions suggest that they are highly primitive and have not experienced reprocessing sufficient to erase their isotopic signatures, yet their absence of  $^{26}\text{Al}$  would seem to indicate younger ages than “normal” CAIs. Do FUN CAIs really separate objects with separate histories from normal CAIs, or did they just form from isotopically-different material? If the former, multiple processes or multiple locations of formation gave rise to remarkably convergent evolution for these two groups of objects. A critical, needed measurement is establishment of an absolute high-precision radiometric age for one or more FUN CAIs, to establish unequivocally their ages relative to normal CAIs. (2) Sorting of CAIs by size into the various chondrite groups is consistent with the X-wind model, but sorting by CAI type is not. Why are Type B and grossite-rich CAIs so restricted in their occurrences, and why do CMs mostly lack melilite-rich CAIs even though tiny melilite-rich CAIs are common in many other chondrite types? For that matter, what are the relationships of the various CAI types to each other—spatial, temporal, and environmental? These are areas in which little work has been done, yet may be critical tests of the X-wind model. (3) It is now reasonably

well-established that chondrules began forming 1–2 My after CAI formation yet, when they did so, few CAIs were present in the chondrule-forming region and those that were consisted mainly of pyroxene + spinel + plagioclase. Where were the melilite-rich and hibonite-rich CAIs during the “chondrule-forming event”, if the X-wind spewed CAIs indiscriminately outward from the sun? How did the CAIs eventually become intimately mixed with chondrules just prior to chondrite accretion?

Finally, here are some miscellaneous thoughts, problems, and unanswered questions. (1) If  $^{16}\text{O}$  and  $^{10}\text{Be}$  both were the products of near-protosun processes, might there be some correlation in the magnitudes of the signatures when measured across CAI and chondrule populations as a result of formation at different heliocentric distances? (2) Virtually all CAIs possess thin multilayered rim sequences on their exteriors, known as Wark-Lovering rims. These rims commonly duplicate phases that are present in the CAI interiors, yet clearly formed in a very different and later event. After 30 years of studying CAIs, workers know a lot about the properties of rim sequences yet the nature of the fundamental and ubiquitous process that the rims represent remains poorly understood. Right now few workers are thinking about why or where the rims formed. (3) The major element compositions of CAIs are almost completely decoupled from their trace element fractionation patterns, but this has never been explained. For that matter, an unnoticed but potentially embarrassing feature of trace element fractionation models is that all of the elemental fractionation occurs within a tiny fraction of one degree in temperature; is this realistic in a nebula setting?

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