FOUR CAI CONUNDRUMS: CHALLENGES FOR FUTURE WORK.

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Introduction: The past 10 years have seen a major renaissance in CAI research and major advances in our understanding of these objects, due in part to advances in analytical technology and in part to an accelerating convergence of cosmochemical models with astrophysical ones. The discovery of extinct ^{10}Be in CAIs [1], together with their mostly consistent initial oxygen isotopic compositions (regardless of chondrite type) and consistent initial ^{26}Al/^{27}Al ratios (with the exception of FUN and related objects), led to the idea that CAIs formed very near the proto-Sun and were later distributed throughout the solar system. The Al-Mg isotopic system has proven to be the most generally-reliable chronometer among those based on short-lived nuclides, and with current analytical precision is capable of resolving time differences as small as 2-5×10^4 years using internal isochrons. The thermal and chemical histories of CAIs are probably better understood than even those of chondrules. Nevertheless, not all is as clear as these statements might suggest. Our purpose here is to highlight four (admitting that there are others) glaring enigmatic issues, some old and some new.

Where did CAIs form? It seems not generally appreciated that there is a fundamental inconsistency with the model (outlined above) for CAIs forming very near the proto-Sun. Recent reviews [2, 3] note that CAIs cannot have formed inside the gap between the infant star and the inner edge of the dust ring: the complete evaporation of all dust concentrated at the nebula midplane would have caused elevated fO_2 inconsistent with the near-solar redox conditions inferred from the presence of trivalent titanium in CAI pyroxenes and hibonites [e.g. 3]. Yet CAIs formed out of a gas of solar chemical (not dust-enriched) and isotopic (oxygen) composition. So where did such an environment exist other than the Sun itself? It cannot have been too distant. Most workers [e.g. 4, 5; but c.f. 6] accept that the ^{10}Be in CAIs formed by solar cosmic ray bombardment near the early Sun, meaning the CAIs formed in that environment as well. The oxygen isotopic compositions of CAIs, being near that of the Sun [7], imply this as well. If the conclusion remains valid that the fO_2 of the dust-free gap was too high to account for CAI pyroxenes (presumably true also anywhere within the dust ring itself if temperatures became high enough to form CAIs), then the implication would seem to be that CAIs formed above or below the central plane of the nebula. This is pure speculation, but the problem is real and needs to be addressed.

What is temporal relationship between O-isotopes and fO_2? CAI pyroxenes and hibonites formed under highly reducing conditions [3], but until recently no time constraints could be placed on the duration of the environment in which they formed. Ultra-high-precision measurements of Al-Mg isotopic compositions have shown that CAI formation (as opposed to primary condensation) extended over a period of at least 2×10^5 years [8]. Yet CAIs that span this age range contain equally-reduced (50–70% Ti as Ti^{3+}) pyroxenes as primary phases. What is most perplexing is that these same reduced pyroxenes from different CAIs differ greatly in their oxygen isotopic compositions, some being very ^{16}O-rich and others being barely enriched in ^{16}O at all [9]. Yurimoto et al [10] proposed that CAIs sampled multiple distinct reservoirs during their primary formation, either as a result of temporal variations in the composition of the gas or because the CAIs were transported to different isotopically-distinct regions, before being accreted into the parent body. If so, we now have the constraint that those separate regions were equally reducing. It is hard to imagine that the ^{16}O-depleted region was inside the dusty disk, since not only would that region have elevated fO_2 but also any silicate dust would have become incorporated into the CAIs at that time; this is not observed. So we have another enigma: how to have isotopically-distinct regions of the nebula from which CAIs formed and evolved, yet those regions must remain not only separate but equally reducing for at least 2×10^5 years.

When did Wark-Lovering rims form? Related to the fO_2 problem above is the origin of Wark-Lovering (WL) rim sequences. The same CAIs that differ in age by 2×10^5 years (above) all have well-developed rims, and it now seems that the pyroxenes in rim sequences contain the same proportion of trivalent titanium as do interior primary pyroxenes [3, 11]. If CAIs continued forming over a long period of time, either their respective WL rims must have formed far apart in time as well or else all WL rims on all CAIs formed at once in one single event, after the formation of the last CAI. The latter alternative is highly unlikely, which means that WL rims are not a single temporal event in the history of the early solar system. They represent an ongoing process that happened at least once to every CAI. It is critical to obtain high-precision Al-Mg isotopic data on rims from a wide range of CAI types and CAI relative ages to prove or disprove this idea. It is equally critical that the valence state of titanium be carefully determined in these same rim pyroxenes.

FUN CAIs and the Stardust Enigma. The existence of FUN (those with fractionation and unidentified nuclear effects) CAIs and isotopically-anomalous platy hibonite crystals (PLACs) in CM chondrites establish beyond doubt that the solar nebula was isotopically-heterogeneous at a grain-to-grain scale. The eternal FUN problem has generally been expressed in terms of why rare (the FUN) CAIs formed with large non-radiogenic isotope anomalies but little or no live ^{26}Al, while others (most CAIs) show the reverse pattern. Less appreciated is the fact that otherwise identical kinds of CAIs formed under identical conditions from reservoirs that were very different isotopically and which never mixed [12, 13]. If CAIs formed and evolved in the nebula for a period of at least 2×10^5 years as noted above, how did the reservoirs remain so separate? Keeping them separate in a gaseous state is unlikely, especially if all CAIs formed in the restricted region very near the Sun. Thus have come various proposals that FUN CAIs are either older or younger than normal CAIs depending on when one thinks ^{26}Al was injected into the solar nebula. For this reason there is an enormous urgency now to find a large FUN CAI and measure a precise U-Pb age for it. However, there may be an alternative model for FUN CAIs that is suggested by observations of material collected by NASA's Stardust mission. Comets presumably accreted in the outermost regions of the solar system, and as such, the expectation was that the material collected from comet Wild-2 would be some of the most primitive and unprocessed early solar system material. Yet detailed studies of the Stardust samples have revealed anhydrous and mostly high-temperature grains similar to those observed in chondrites [14]. More curious is the finding that *bona fide* presolar grains (defined as having extreme isotopic compositions) are very rare. Finally, two CAIs have been found that both lack any evidence for extinct ^{26}Al [15]. The orthodox explanation for these observations is that transport of materials in both directions between the innermost solar system and the comet-accreting region was extremely efficient. In essence, virtually no presolar material was preserved in the outermost solar system. Based purely on a reasonability argument, this seems unlikely. Pre-solar grains are identified by their extreme isotopic compositions, which come directly from nucleosynthetic sources such as supernovae and red giant stars. Grains from other sources might not be recognized simply because their isotopic compositions are not extreme. Consider for example young stellar objects experiencing bi-polar outflow. If our Sun was formed in a giant molecular cloud like Orion, it would have been in close proximity to many other infant stars, some a bit older and others a bit younger, all formed out of the same cloud and all have broadly similar bulk compositions. The difference is that some would have formed significantly prior to the explosion of a massive O or B star in the center of the cluster, which in turn would have embedded freshly-synthesized ^{26}Al into our own nascent solar system. Those earlier solar systems would have seeded – via bi-polar outflow – the nearby cloud with grains processed near their own suns, including CAIs and silicate grains similar to those made in our solar system but with subtle isotopic variations (no ^{26}Al; only small differences in nuclear anomalies). Tielens et al. [16] estimate that as much as 30% of interstellar grains derive from young stellar objects. In the triggered star-forming walls of a giant HII region, that fraction could easily be much higher. Thus we suggest it is at least worth considering the possibility that FUN CAIs and some (many?) of the Stardust grains did not come from within our solar system at all but rather *via* bi-polar outflow from sister stars to our Sun, formed around the same time. They are presolar by definition, but currently cannot be recognized as such.

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