WHENCE CAIs? FROM BEYOND JUPITER, FROM THE YOUNG SUN, OR FROM A SIBLING STAR?

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Introduction: Brennecka et al. [1] made the thought-provoking suggestion that the fine-grained calcium-aluminium-rich inclusions (CAIs) in the Allende CV3 chondrite condensed in the outer solar system, beyond the orbit of Jupiter, since they have Mo isotope signatures that spread along the well-defined ‘carbonaceous chondrite’ or ‘outer solar system’ line on an ε^{94}Mo v ε^{95}Mo diagram [2]. They tentatively suggested that the heat source may have been a hot proto-Jupiter, and that an origin for CAIs in this distal part of the disk is consistent with their prevalence in carbonaceous chondrites whose parent bodies accreted in this region. Their conjecture is a radical departure from the ‘standard model’ for CAI formation [3, 4], close to the protosun, so it calls for careful scrutiny and it also prompts a more general enquiry into how and where CAIs were most plausibly produced.

Here, we suggest that the Mo isotopic signature of the Allende fine-grained CAIs may be a late imprint, rather than an original feature, and was inherited from the meteorite matrix when Mo was mobilized during hydrothermal metamorphism on the parent body. In this case it would have no bearing on where the CAIs were made. We then summarize our understanding of the ‘standard model’ in which CAIs were produced close to the young Sun. Finally we speculate that CAIs may not, in fact, come from the solar system, but may come, instead, from the outflows of a sibling star (or sibling stars) in a long-vanished cluster to which the young Sun initially belonged.

Mo isotopes in Allende fine-grained CAIs: We wonder whether the Mo isotope pattern in the CAIs is a secondary feature for several reasons. 1) Allende is believed to have been affected by substantial hydrothermal alteration within the parent body. 2) The spread of ε^{94}Mo values, from -20 (s-process excess) to +17 (s-process deficit) is enormous [5], and well beyond the range for bulk meteorites, whereas CAIs condensed from a locally produced hot gas might be expected to be rather uniform and similar to that of bulk meteorites. 3) The spread is on the same line as, but less extensive than, that seen in leachates from bulk Murchison (CM2) (ε^{94}Mo is -65 to +25) [6] which is presumably a mixing line between easily dissolved pre-solar grains (s-deficit) and insoluble pre-solar grains (s-excess) in the matrix. 4) Mo is one of the few elements that varies in concentration among CM chondrites. The variation is linked to the degree of aqueous alteration, and is presumed to reflect redox-controlled solubility [7]. Mo is also known to be mobile during hot desert weathering [8]. 5) There may have been very little Mo in the original fine-grained CAIs since metal-bearing phases are rare in them [5], so any that was present might have been swamped by Mo brought in from outside. 6) Allende matrix has been analysed for Mo isotopes [2] and has the same s-process excess signature as that seen in all but one of the fine-grained CAIs analysed by [1]. 7) For most elements, particularly lithophile elements, isotopic anomalies are the same in both fine-grained and coarse-grained CAIs [5, 8], so Mo in Allende CAIs stands out as being odd.

If our suspicions are valid, then how did the fine-grained CAIs end up so vastly different from each other in terms of their Mo isotopes? We do not know the answer. Perhaps the Mo that was mobilized from the matrix first and most readily (s-process deficit) during metamorphism was mopped up by secondary crystals that nucleated and grew in just one of the CAIs, while the other four CAIs (which are s-process enriched) developed other secondary minerals that incorporated Mo that was released later.

The ‘standard model’ for CAI formation: While we do not believe that CAIs were made beyond Jupiter, the suggestion that they were [1] is refreshing and has encouraged us to think more about where CAIs may have been made. Wood [3] presented a personal view of the astrophysical setting for CAI formation which has been widely adopted as the ‘standard model’. To quote [3], ‘The innermost portion of the sun's rapidly accreting nebular disk, kept hot during that period by viscous dissipation, is the most plausible site for CAI formation. Once condensed, CAIs must be taken out of that hot zone rather promptly in order to preserve their specialized mineralogical compositions, and they must be transported to the radial distance of the asteroid belt to be available for accretion into the chondrites that contain them today. Though this paper is critical of some aspects of the x-wind model of CAI formation, something akin to the x-wind may be the best way of understanding this extraction and transport of CAIs.’.

New data since [3], reviewed by [4], has refined and reinforced the ‘standard model’. For example, CAIs are enriched in ^{16}O by an amount which is now known to closely match that of the Sun, based on measurements of oxygen isotopes in the solar wind [9]. Wood [3] emphasised the brief duration of CAI formation, and it now seems likely that most CAIs condensed from hot gas of solar composition in less than 20,000 years [10]. This is about the same duration as the period for which the newborn Sun would have been a Class 0 young stellar object

(YSO), while it was growing rapidly and deeply embedded in its thick envelope of in-falling molecular cloud material. About 10% of the accreting material would have been returned to space as bipolar ‘outflows’ of hot gas, which is presumably where the CAIs condensed.

The newly-made CAIs contained short-lived ^{26}Al with ^{26}Al/^{27}Al uniformly at the so-called canonical value of 5.23 x 10^{-5} [10]. This and other short-lived isotopes were probably mixed into the molecular cloud from a nearby supernova during, or even causing, collapse of the molecular cloud.

Internal Al-Mg isochrons imply that some of the original CAIs were re-heated, causing melting and partial evaporation over the subsequent 200 to 500 kyr [11], but how and where this occurred is not known. Nor is it known how the CAIs were transported far from the Sun, nor how they were preserved for some 2 to 3 Myr before they accreted to chondritic bodies.

A few rare CAIs called FUN CAIs have unusual isotopic anomalies and little or no former ^{26}Al [e.g. 12]. These remain puzzling; it is presumed that the ^{26}Al was added to the molecular cloud while it was collapsing and the infant Sun was growing, and that the FUN CAIs condensed from outflows launched before the admixture of the ^{26}Al.

Could CAIs have come from a sibling star to the young Sun? Most stars form in clusters, and not in isolation. Reipurth [13] stated ‘The meteoritic record must be examined with the possibility in mind that the early Sun may well have been a member of a long gone cluster and that the early solar nebula may have been affected by close passages of sibling stars’. Evidence consistent with this possibility is that the rotation axis of the Sun is tilted 7° to the rotation axis of the planetary orbits, and that the solar system is truncated at the Kuiper belt [13]. Co-accretion of stars in clusters, with chaotic changes to orbits, is monitored in real time by observations of clusters of protostellar outflows and jets [14]. Stellar clusters are also a feature of numerical modelling of cloud collapse, as the online animations produced by Matthew Bate testify [astro.ex.ac.uk].

However, all young stars in a cluster presumably would have been formed at the same time, and would have shared the same elemental isotopic compositions, to a good approximation. In this case it would not be possible to tell from the ages and the isotopic signatures of CAIs whether they originated from the young Sun or from one or more of its siblings.

Nevertheless, the protostars in a cluster would presumably have been generating stellar outflows in tandem, with a massive 10% of accreting gas and dust being returned as hot gas with CAI condensates to the surrounding cloud while it was still collapsing. Since the protostars were gravitationally bound and orbiting each other in a chaotic manner, we wonder whether the disk around any one star might have become ‘polluted’ by the CAIs in an outflow from another star as it passed close by. In this light, we suggest that perhaps stellar outflows from sibling stars provide a plausible alternative to x-winds from the young Sun for delivering CAIs to the outer parts of the solar nebula.

Another advantage of the idea that CAIs could have come from a sibling star is that it provides a different explanation for FUN CAIs. In this case the sibling star would have grown from a part of the cloud that somehow escaped the injection of ^{26}Al, and the required heterogeneity in the cloud would simply be spatial, and not temporal.

Spatial, not temporal, variation in the molecular cloud might also have a bearing on ‘normal’ CAIs which, in general, and regardless of whether they are coarse- or fine-grained, have an isotopic signature for each element which is resolvable, in terms of nucleosynthetic anomalies, from that of the planets and bulk meteorites of the solar system [8]. While this difference has been attributed to changes in the material accreting to the young Sun through time, it could plausibly be the signature of a sibling star, nearby in space.

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