Whence CAIs?
From beyond Jupiter, from the young Sun, or from a sibling star?

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Brennecka et al. [1] made the tantalising suggestion that the fine-grained CAIs in Allende (CV3) were perhaps formed in the outer solar system, beyond the orbit of Jupiter, since these CAIs 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] (Fig. 1). Kleine et al. [3] developed the suggestion by speculating that the CAIs were, instead, made close to the Sun in a proto-CC reservoir that occupied the inner solar system and was later transported outwards and diluted with in-falling material to become the CC reservoir.

Here we suggest that the CC signature of Mo isotopes in the CAIs is not an original feature, but was acquired by the CAIs from presolar grains in the matrix during aqueous alteration on the Allende parent body. We believe it has no bearing on where the CAIs were made.

With our curiosity about CAIs raised, we continue here by trying to understand the astrophysical setting for CAI formation, and conclude that (at least some) CAIs plausibly come from the Sun's sibling stars.

Evidence that Mo isotopes in Allende fine-grained CAIs are derived from the matrix

1. The Allende fine-grained CAIs span a wide range of Mo isotopic compositions, far exceeding the range for bulk meteorites (Fig. 1). If they had condensed from a hot CC-like vapour, they would surely be isotopically rather similar to each other.
2) Allende has undergone major parent-body aqueous alteration [4], and Mo is mobilized in aqueous solution, e.g. in CM chondrites [5] and on Earth [6].
3) As [1] pointed out, Fig. 1 shows that the spread of the Mo CAI data closely follows the data for Mo isotopes in step-wise acid leachates from Murchison (CM2). We suggest that similar leaching of Mo happened naturally in the Allende parent body during metamorphism. We suspect that the dissolved Mo was taken up differently by secondary minerals in the fine-grained CAIs.
4) Coarse-grained (igneous) CAIs in Allende plot together, well above the CC line (Fig. 1). Some such CAIs have Type-II REEs so would have been fine-grained CAIs initially, and then been melted. Having two separate kinds of fine-grained CAI seems unlikely.
5) All CAIs have a 'solar' oxygen isotope pattern. The CC reservoir does not.

Features of CAIs and their inferred origins

CAIs are widely believed to have formed close to the very young Sun, for the following reasons:

1) Their mineral constituents are refractory and match what is thermodynamically predicted to condense first from a very hot gas of solar composition [4].
2) Their oxygen is isotopically unlike that in planets and bulk meteorites, and very like that of the Sun [7].
3) They were irradiated by solar cosmic rays at close range based on evidence of extinct ^{10}Be [e.g. 8].

Other important features of CAIs are:

4) Precise Pb-Pb dating of CAIs shows they are 4567-4568 Myr old, making them the oldest solar system solids.
5) The hot gas from which most CAIs condensed contained ~52 atoms of ^{26}Al for every million atoms of ^{27}Al [9]. The ^{26}Al was probably derived from a nearby Wolf-Rayet or massive star just before, or actually triggering, collapse of the pre-solar cloud [10].
6) Most CAIs have this level of ^{26}Al so evidently condensed simultaneously in <20,000 years [11].
7) A few CAIs (FUN CAIs) evidently contained little or no initial ^{26}Al. These are puzzling; perhaps they condensed from hot gas before ^{26}Al was added. Who knows?
8) Many CAIs were reprocessed (melted, aggregated, partly evaporated), over the first 200 kyr or more [12].
9) CAIs are nearly all found in carbonaceous chondrites whose parent bodies accreted probably in the disc beyond the orbit of Jupiter (CC reservoir), more than 2 million years after the CAIs had formed [13].
10) CAIs are isotopically broadly alike, and though similar to bulk meteorites, differ from them in detail [14].

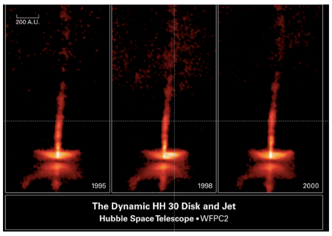

Fig. 2. Bipolar outflows: could these be the CAI factory?

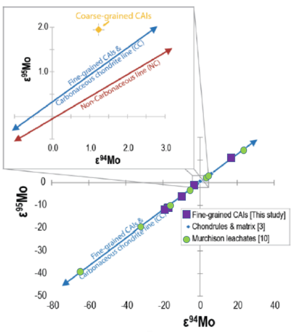

Fig. 1. A copy of the diagram presented by [1], with data for the fine-grained CAIs in purple and the leachates from Murchison [3] in green.

Linking CAI formation with star formation: Could CAIs come from the Sun's sibling stars?

1) Some 10% of matter that falls onto a growing protostar is ejected in polar outflows (Fig 2) [15]. Perhaps CAIs condensed within such hot outward-streaming gas.
2) This gas will have had the oxygen isotopes of the protostar (not of the dust in the collapsing cloud).
3) Most of the in-fall (and hence outflow) happens quickly, over ~10,000 years while the protostar is a Type 0 young stellar object. Such a timescale is consistent with the <20,000 years duration of CAI formation.
4) The Sun, like most stars, was probably born in a cluster of co-orbiting same-age siblings (Fig. 3) with similar chemical and isotopic compositions [16]. Thus, outflows from those siblings would have polluted the surrounding protostellar cloud with isotopically similar (perhaps not quite identical) CAI condensates, some of which would, perhaps, have ended up in the protosolar disc (Fig. 4). This is not a new idea [17, 18]. It obviates the need for x-wind or other transport from the Sun.
5) CAIs falling onto the disc beyond Jupiter's orbit (Fig. 4) and migrating inwards would be held up at the 'Jupiter gap', accounting for their relative abundance in carbonaceous chondrites [13].
6) FUN CAIs might be wandering vagrants from more-distant protostars in parts of the cloud that escaped the injection of ^{26}Al.
7) One setting for reworking CAIs ~200 kyr after formation is frictional heating as CAIs from another star's outflow enter the gassy disk at high speed.
8) Close passage of co-orbiting sibling stars (Fig. 3) can give rise to other ways of producing, and delivering CAIs, which have yet to be explored [e.g. 19].

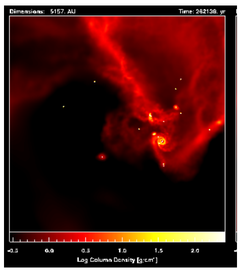

Fig. 3. Screen shot of animation of a numerical simulation of star formation in a huge cloud of gas and dust. New stars are co-orbiting in tight clusters. (Matthew Bate www.youtube.com/watch?v=3z9ZKAkbMhY)

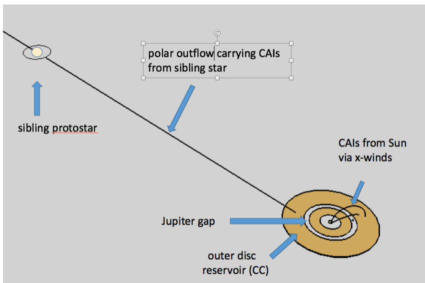

Fig 4. Cartoon showing delivery of CAIs to the outer disc from the outflow of a sibling star as an alternative to other ways of delivery such as putative disk winds.

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