

CAIs DID NOT FORM IN THE OUTER SOLAR SYSTEM. G. J. MacPherson (macphers@si.edu). Dept. of Mineral Sciences, MRC-119, Museum of Natural History, Smithsonian Institution, Washington D.C., USA 20560.

Introduction: Ca-Al-rich inclusions (CAIs) uniquely record the processes and conditions that existed during the first ~1 m.y. of our Solar System's existence. Nearly 50 years of world-wide research on CAIs has led to general agreement that they formed in the pre-solar nebula at very high temperatures under exceedingly reducing conditions, and especially that they formed very close to the proto-Sun in the inner Solar System. Nevertheless, there have been recent suggestions that CAIs might actually have formed in the outer Solar System. Such suggestions have been made in seeming oblivion of cumulative isotopic, experimental, and petrologic evidence to the contrary. The goal here is to lay to rest any idea that CAIs formed in the outer Solar System

As background, the controversy started in 2011 when Warren [1] highlighted the exceptional dichotomy of chondritic meteorites in terms of the non-radiogenic isotopes $\epsilon^{54}\text{Cr}$, $\epsilon^{50}\text{Ti}$, and $\epsilon^{62}\text{Ni}$. Because carbonaceous chondrites are isotopically distinct from all other chondrite types, he argued that carbonaceous chondrites formed in a different nebular location than did other chondrites. He then speculated that the carbonaceous chondrites formed in the outer Solar System (defined as being exterior to Jupiter's orbit) whereas other chondrites formed in the inner Solar System. But note that Warren's idea was based on whole-chondrite compositions only: He did *not* comment on where CAIs (or chondrules) formed. During the ensuing 8 years, numerous detailed and highly precise isotopic studies have confirmed the "isotope gap" between carbonaceous vs. other chondrites. Unlike [1], some of these studies have concluded that CAIs themselves formed in the outer Solar System, and this is where the problem lies. The data are not in question, but the interpretation is.

^{10}Be : It was shown by [2] that CAIs contained the short-lived radionuclide ^{10}Be when they formed. Unlike ^{26}Al , ^{10}Be is not derived from stellar nucleosynthesis but, rather, by cosmic ray spallation. For this reason [2] (and later, [3] and others) concluded that the CAIs must have formed near the infant proto-Sun where they were bombarded by solar cosmic rays. This remains one of the strongest arguments that CAIs formed in the inner solar system:

Oxygen fugacity: A principal component of many CAIs is calcium-rich clinopyroxene that is also titanium-rich. In all cases, approximately $\frac{1}{2}$ of the total titanium is trivalent. J. Beckett showed experimentally (see [4]) that this circumstance requires extremely re-

ducing conditions, approximately 8 log units below the iron-wüstite buffer. This is equivalent to a hot gas of solar composition, i.e. hot hydrogen, and is much more reducing than conditions under which oxidized iron is abundant, as for example in chondrules [4]. As emphasized by [4], CAIs are the *only* chondritic material to have formed in an environment of near solar composition. This points to a region of the nebula separate from where chondrules and other chondritic components formed, i.e. *not* the outer solar system.

CAIs formed in a region mostly devoid of other materials: CAIs only rarely contain inclusions of chondrule fragments or other chondritic materials, and the ones that do are of an unusual variety called Type C (e.g. [5]). This observations indicates that CAIs formed in a nebular region that contained only refractory solids, arguably the inner solar system where temperatures were too high for other components to condense.

CAIs have the oxygen isotopic composition of the Sun: The seminal discovery that CAIs are ^{16}O -rich [6] led to the discovery of other isotope anomalies in CAIs. The ^{16}O -rich component in CAIs was interpreted by [6] as residual from the pre-solar solids that were precursors to the CAIs. In this early model, solar nebular solids were thought to be ^{16}O -rich and the gas was ^{16}O -poor. The subsequent discovery that pre-solar grains in chondrites are mostly *not* ^{16}O -rich upended this model. But the most critical finding, based on analysis of returned samples from the Genesis mission, was that the Sun itself *is* ^{16}O -rich and, in fact, close to the compositions of most CAIs [7]. This means that CAIs (or their precursors), and *only* CAIs, formed in a gas of Solar oxygen isotopic composition. This inextricably links CAIs to the immediate solar environment - the innermost solar system - at the time of their formation

Heliocentric distance and oxygen isotope mixing lines: Some speculations: The Carbonaceous Chondrite Anhydrous Minerals line (CCAM) was originally defined by a combination of bulk anhydrous carbonaceous chondrites, their anhydrous silicate minerals, and especially CAIs and their constituent minerals. Most CAIs started out as uniformly ^{16}O -rich with compositions at $\delta^{17}\text{O} = \delta^{18}\text{O} = \sim -50\text{--}60\text{‰}$, but those in CV and CO chondrites experienced later partial exchange with a gas that was not ^{16}O -rich. Thus individual CAI minerals disperse along CCAM. But a curious feature of this mixing, long known but little discussed, is that if

FUN CAIs and their minerals are plotted on a 3-isotope diagram along with normal CAIs (Fig. 1), they do not plot along the same mixing line (CCAM). Rather, they define independent mixing lines that all intersect at a common point that does lie on CCAM, close to but distinctly below the terrestrial fractionation line (TF). This composition, highlighted by the green circle on Fig. 1, is singular because it does not correspond to any other notable solar system composition. Quite simply, it represents the gas composition with which CV/CO CAIs exchanged following their formation (and not on a parent body, PB, which produces slope- $\frac{1}{2}$ lines). But other chondrites and chondrite components did not exchange with such a gas. Rather, they each exchanged with separate gas compositions. This is illustrated in Fig. 2, where the bulk isotopic compositions of H, L, LL, Rumuruti, and primitive achondrites, plus ureilites, are plotted on a 3-isotope diagram. Each of these groups define linear arrays whose slopes are not within error of $\frac{1}{2}$. Thus they are mixing lines, but mixing between what? One can assume that the original solids were at the ^{16}O -rich ends of the mixing lines, but there is nothing beyond the ^{16}O -poor ends of the arrays except for an extension of the CCAM line above the TF line. Accordingly, I have extrapolated the mixing lines of each of the groups plotted on Fig. 2 to intersect with the extended CCAM line. Excepting ureilites, which overlap with CV3 chondrites, each of the groups intersect with CCAM at a different point (composition) that is nowhere near the CAI exchange point of Fig. 1. Consider this observation in the context of what CCAM itself currently is thought to represent: a solar gas – evaporated ice mixing line. Sakamoto et al. [8] discovered exceptionally ^{16}O -depleted grains in a primitive chondrite, which they interpreted to represent the composition of outer solar system ice. Krot et al. [9] interpreted the CAI portion of CCAM to be exchange of ^{16}O -rich CAIs with an ^{16}O -poor gas that owed its composition to inward nebular drifting of outer solar system ice. If their overall model is basically correct, it suggests the CCAM has a heliocentric significance. Admitting of course that the nebula was turbulent, nevertheless there is a suggestion that in a crude way the nebular gas was more ^{16}O -depleted with increasing distance from the Sun (higher proportion of evaporated ice to solar gas). It then follows from Fig. 2 that, if my exchange model is correct, non-carbonaceous chondrites exchanged with a gas that was ^{16}O -depleted relative to that with which anhydrous carbonaceous chondrites exchanged. This would mean that non-carbonaceous chondrites were *more* distant from the Sun than carbonaceous chondrites. *This is exactly opposite to what the model of [1] posits.* Taken together with the arguments sum-

marized above, I conclude that not only did CAIs form in the inner solar system, their host chondrites formed interior to where non-carbonaceous chondrites formed. The isotope dichotomy between carbonaceous vs. non-carbonaceous chondrites did not result from CAIs forming in the outer solar system, and maybe not carbonaceous chondrites themselves.

References: [1] Warren P. H. (2011) *EPSL* 311, 93–100; [2] McKeegan K. D. et al. (2000) *Science* 289, 1334–1337. [3] MacPherson G. J. (2003) *GCA* 67, 3165–3179. [4] Grossman L. et al. (2007) *Rev. Miner. & Geochem.* 68, Ch. 7. [5] Krot A. N. et al. (2007) *MAPS* 42, 1197–1219. [6] Clayton R. N. (1973) *Science* 182, 485–498. [7] McKeegan K. D. et al. (2011) *Science* 332, 1528–1532. [8] Sakamoto et al. (2007) *Science* 317, 231–233. [9] Krot, A.N. et al. (2010) *Ap. J.* 713, 1159.

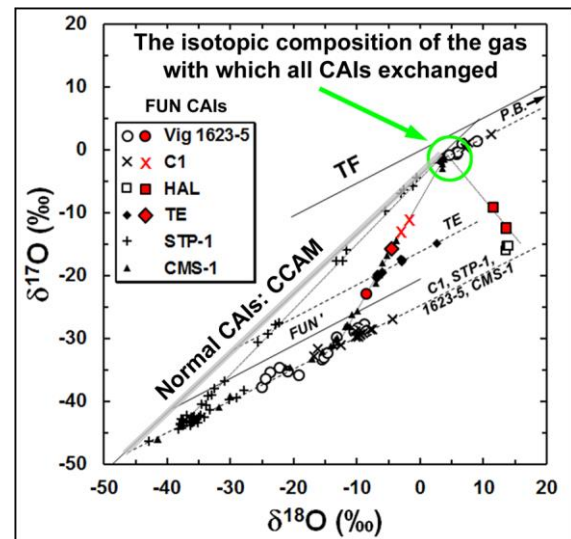


Figure 1.

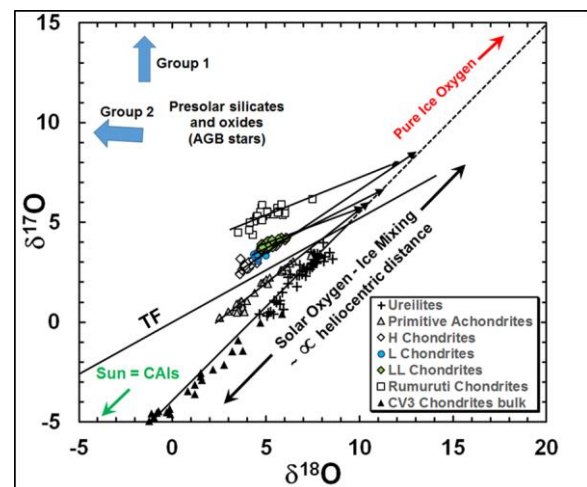


Figure 2.