

Calcium-Aluminum-Rich Inclusions Are Not Supernova Condensates

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Abstract. Supernovae eject material into the interstellar medium that is highly heterogeneous and highly non-solar in isotopic composition. In contrast, calcium-aluminum-rich inclusions (CAIs) in primitive meteorites have isotopic compositions that are very similar to those of the bulk Earth and Solar System and, for most elements, to each other. Thus, a recent suggestion that CAIs formed originally as supernova condensates is untenable.

1. Introduction

Calcium-aluminum-rich inclusions or CAIs are a major constituent of many classes of primitive meteorites (MacPherson 2003). They are sub-mm to cm-sized assemblages of different refractory Ca and/or Al-rich minerals (e.g., spinel, mellilite, hibonite, etc.) and have been the focus of intense study for decades. They are the oldest objects in the Solar System that have been dated using radiogenic isotope techniques and often contain isotopic “anomalies:” differences in isotopic ratios from other Solar System materials that cannot be explained by common chemical or physical fractionation processes. These observations and their refractory natures are commonly interpreted as indicating that they were among the first solid materials that formed in the Solar System.

In recent abstracts and papers (Cameron 2003; Cameron & Lodders 2004; Lodders & Cameron 2004, Cameron, this volume), A. G. W. Cameron has suggested that rather than forming in the early Solar System, CAIs in fact condensed in the ejecta of presolar supernova explosions, and became part of the molecular cloud from which the Sun, Earth and other planets formed. More specifically, he postulates that the CAIs we observe formed by re-heating in the solar nebula of similarly sized, pre-existing objects (“proto-CAIs”) that condensed in well-mixed and homogenized supernova ejecta. Cameron (2003) suggested that all CAIs formed in a single supernova, assumed also to trigger the collapse of the protosolar cloud. More-recent work has proposed that the inclusions formed in a large number of supernovae over a long period of time (Cameron, this volume). Here I demonstrate that current understanding of supernova nucleosynthesis and mixing is inconsistent with such an origin for CAIs.

2. Stable Isotopes

CAIs are often referred to as ^{16}O -rich. This refers to the fact that, by and large, individual minerals within CAIs have $^{17}\text{O}/^{18}\text{O}$ ratios closely similar to that of ocean water, but $^{17}\text{O}/^{16}\text{O}$ and $^{18}\text{O}/^{16}\text{O}$ ratios lower than the terrestrial ratios (Clayton, Grossman, & Mayeda 1973; MacPherson 2003). The largest ^{16}O enrichments (~4-5%) are usually observed in spinel (MgAl_2O_4). At the time of the discovery of this O “anomaly” (Clayton et al. 1973), all known physical and chemical processes that fractionate O isotopes did so in a mass-dependent fashion. Such processes affect ^{18}O twice as much as ^{17}O , and there is a resulting fractionation in the $^{17}\text{O}/^{18}\text{O}$ ratio. The constant $^{17}\text{O}/^{18}\text{O}$ ratio of CAIs thus was interpreted as most likely reflecting an admixture of ^{16}O -rich material, probably a nucleosynthetic effect. Since Type II supernovae (those produced by core-collapse of evolved massive stars) produce copious amounts of ^{16}O , it was thought that perhaps CAIs reflected partial preservation of ^{16}O -rich dust produced in one or more presolar supernovae. Such an origin for the CAI O isotopic compositions has fallen out of favor in recent years for a number of reasons. First, when *bona fide* O-rich presolar grains of stardust were finally identified within meteorites, they were found to be on average ^{17}O -rich, not ^{16}O -rich (Huss et al. 1994; Nittler et al. 1997). Second, it is now known that some chemical processes can fractionate O isotopes in a mass-independent way, leading to ^{16}O -rich and ^{16}O -poor compositions with relatively constant $^{17}\text{O}/^{18}\text{O}$. These include photochemical gas-phase processes known to take place in the earth’s upper atmosphere (Thiemens 2001) and self-shielding of CO from ultraviolet photo-dissociation in molecular clouds (Yurimoto & Kuramoto 2004) and/or the early Solar System (Clayton 2002). Thus, nuclear effects are not required to explain the CAI data.

Recently, Cameron (2003, this volume) has resurrected the idea of a supernova link to CAIs. Although his primary argument is based on the abundances of extinct radionuclides (e.g., ^{26}Al) in CAIs, relative to other planetary materials, he also suggests that the ^{16}O -richness of the inclusions supports a direct link to supernovae. For example, Cameron & Lodders (2004) state that “supernova stars produce an excess of ^{16}O and the lower mass stars have a counterbalancing deficit of this nuclide.” In fact, modern understanding of nucleosynthesis indicates that the situation is considerably more complicated. Although most supernova models assume an initially solar composition, this composition is largely erased by nucleosynthesis and mixing throughout a massive star’s life. By the time a massive star explodes as a Type II supernova, nowhere within the ejecta is predicted to have close-to-solar O isotopic ratios. For example, there is a large envelope enriched in ^{17}O from H burning, a region with enhanced ^{18}O from He burning, and interior zones consisting of almost pure ^{16}O . The predicted surface ^{17}O enrichment of massive stars has been confirmed by spectroscopic measurements of the red supergiants Betelgeuse and Antares (Harris & Lambert 1984). The explosion itself causes some level of mixing of the ejecta (see Section 4), but stellar evolution models coupled with nucleosynthesis networks make it clear that supernova ejecta has highly non-solar O isotopic composition, both in different regions and in bulk.

Figure 1 compares the O isotopic ratios predicted for bulk ejecta of type II supernovae of different initial masses with the O isotopic composition of CAIs. Far from being uniformly rich in ^{16}O , supernovae are predicted to eject material with a

very wide range of highly non-solar O isotopic ratios. In contrast, the CAIs are remarkably uniform in isotopic composition and very close to the terrestrial composition. Except for the lowest mass ($11M_{\odot}$) model, supernovae are predicted to have lower-than-solar $^{17}\text{O}/^{16}\text{O}$ ratios, but $^{18}\text{O}/^{16}\text{O}$ ratios ranging from 0.01 to 10 times the solar value. Only the most massive supernovae are ^{16}O -rich and interpolation of the plotted supernova yields indicates that only those stars with mass somewhere between 25 and $30 M_{\odot}$ have $^{17}\text{O}/^{18}\text{O}$ ratios similar to CAIs. The average supernova ratios, weighted over a Salpeter (1955) initial mass function are also shown in Figure 1. Clearly, supernovae can account for much of the ^{18}O observed in the Solar System, but other stellar sources are needed to explain the solar ^{17}O abundance, most likely novae and intermediate mass asymptotic giant branch stars (Prantzos, Aubert, & Audouze 1996; Romano & Matteucci 2003).

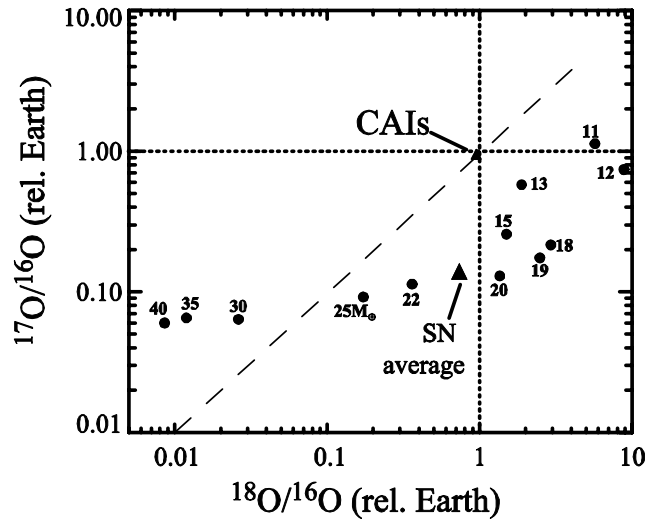


Figure 1. Predicted O isotopic ratios for bulk Type II supernova ejecta, relative to terrestrial ocean water ($^{17}\text{O}/^{16}\text{O}=0.000383$; $^{18}\text{O}/^{16}\text{O}=0.002$), are compared with the almost-solar composition of CAIs. The initial compositions of the stars were assumed to be solar. Filled circles are compositions of supernovae of indicated masses, taken from the calculations of Woosley & Weaver (1995) with ^{17}O and ^{18}O yields multiplied by 0.125 and 0.5, respectively, to take into account updated reaction cross sections (Rauscher et al. 2002). The long-dashed line indicates the correlation line on which individual CAI minerals plot. The average of the supernova yields, weighted by a Salpeter (1955) initial mass function is also indicated.

Figure 1 makes it abundantly clear that CAIs cannot be pristine supernova condensates, or they would have much more anomalous O isotopic compositions. However, let us consider the possibility that the CAIs formed as “proto-CAIs” in super-

nova ejecta and subsequently were melted in the early Solar System with isotopic exchange with nebular gas diluting the pure supernova isotope signatures. In this scenario, the resulting CAI compositions would lie on mixing lines between the solar nebula composition and the supernova compositions. The nebular O isotopic composition is not yet well known, but given the relatively restricted range of O isotopic ratios in bulk planetary materials (meteorites, Earth, Moon, Mars), it was almost certainly highly homogeneous compared to the range of supernova compositions. Thus, CAIs from supernovae of a given initial mass would lie on a single mixing line, but those forming in supernovae with different initial masses would form distinct lines on an O 3-isotope plot. Because all CAIs essentially lie along a single O isotope line and have a very restricted range of compositions (<10%), the isotope data argue strongly against formation of CAIs from protoCAIs that condensed in different supernovae, or one would expect a broader distribution of O isotope data among different CAIs. Of course, this does not preclude formation of all protoCAIs from a single supernova that does plot on a single mixing line with CAIs and the solar composition. Problems with this scenario are discussed below in Section 5.

The above discussion focused on O isotopes, but similar arguments can be made based on other isotopic systems, which in general show much smaller variations in CAIs than do the O isotopic ratios. For example, the Si and Mg isotopic ratios (excluding ^{26}Mg from decay of ^{26}Al , see below) show a very limited range in most CAIs and are closely similar to terrestrial ratios. As in the case of the O isotopes, however, the isotopes of these elements are made in different amounts in different regions of supernovae and in supernovae of different mass. Figure 2 compares the Si isotopic ratios predicted for type II supernovae of different masses with those measured in CAIs. Just as we saw with O, no supernova has a bulk Si isotope composition comparable to the CAIs and CAIs thus cannot be made from pure supernova material. A similar situation obtains for Mg and many other elements.

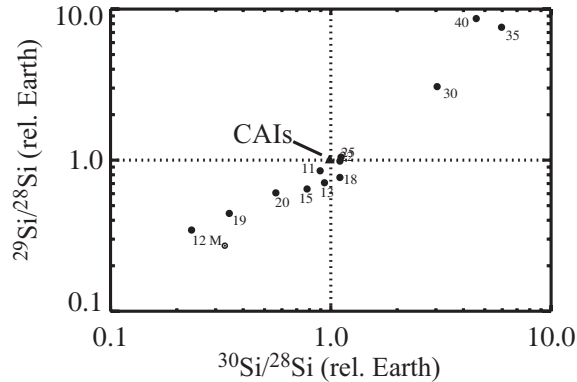


Figure 2. Predicted Si isotopic ratios for bulk Type II supernova ejecta, relative to terrestrial composition ($^{29}\text{Si}/^{28}\text{Si}=0.0506$; $^{30}\text{Si}/^{28}\text{Si}=0.0335$) are compared with the composition of CAIs. Filled circles are compositions of supernovae of indicated masses, taken from the calculations of Woosley & Weaver (1995) with ^{29}Si yields multiplied by 1.5 to match on average the solar $^{29}\text{Si}/^{30}\text{Si}$ ratio (Lugaro et al. 1999).

3. Aluminum-26

Many CAIs have excesses in ^{26}Mg , relative to terrestrial $^{26}\text{Mg}/^{24}\text{Mg}$ ratios without accompanying effects in ^{25}Mg . Moreover, minerals with higher Al/Mg ratios (e.g., anorthite) tend to have higher $^{26}\text{Mg}/^{24}\text{Mg}$ ratios than minerals (e.g., spinel) with lower Al/Mg ratios. These data are clear evidence that at the time the inclusions solidified, they contained live radioactive (half-life $\sim 720,000$ yr) ^{26}Al , which subsequently decayed to ^{26}Mg (Lee, Papanastassiou, & Wasserburg 1976; MacPherson, Davis, & Zinner 1995). Plotting the excess $^{26}\text{Mg}/^{24}\text{Mg}$ versus Al/Mg ratios for different minerals in a CAI yields a straight line (“isochron”) whose slope gives the ratio of ^{26}Al to ^{27}Al present when the inclusion solidified. A huge quantity of ^{26}Al data exists now for CAIs and most CAIs with evidence for ^{26}Al are inferred to have had $^{26}\text{Al}/^{27}\text{Al} \approx 4.5\text{--}5 \times 10^{-5}$ when they formed, the so-called “canonical” ratio (MacPherson et al. 1995). It is unknown whether the inclusions without evidence for ^{26}Al formed without the radioisotope or subsequent processing on the meteorite parent asteroids erased an originally anomalous Mg isotope signature. In any case, like we saw above for O isotopes, CAIs are characterized by a relatively homogeneous inferred initial Al isotopic composition. Is this consistent with a supernova origin for CAIs or their precursors?

Supernovae are indeed prodigious producers of ^{26}Al (and other radioactivities). The ^{26}Al is made by proton captures on ^{25}Mg , partially during core and shell H-burning, but mostly in the Ne-rich zone during hydrostatic shell C-burning (Woosley & Weaver 1995). In fact, models predict that supernovae produce Al with $^{26}\text{Al}/^{27}\text{Al}$ ratios much higher than the canonical CAI value of 5×10^{-5} . For example, the calculations of Rauscher et al. (2002) predict bulk $^{26}\text{Al}/^{27}\text{Al}$ ratios of 5.7×10^{-3} and 3.2×10^{-3} for the ejecta of $15M_{\odot}$ and $25M_{\odot}$ supernovae, respectively. Thus, as we saw for O isotopes, CAIs can not be pure supernova condensates or they would have inferred $^{26}\text{Al}/^{27}\text{Al}$ ratios many times higher than is observed.

If instead CAIs originally condensed in supernovae as protoCAIs and then were re-melted and solidified in the early Solar System, the melting events would have reset the CAI isochrons, such that the inferred $^{26}\text{Al}/^{27}\text{Al}$ ratios indicate the amount of live ^{26}Al present at the time of the melting. Thus, the lower $^{26}\text{Al}/^{27}\text{Al}$ ratios in CAIs compared to pure supernova ejecta could be explained by either radioactive decay during the time intervals between the formation of the protoCAIs and the re-melting events and/or by isotopic exchange with nebular gas during the melting. In either case, it is difficult to envision how such a scenario could plausibly lead to the Al isotopic uniformity observed in CAIs. To explain the sharply-peaked $^{26}\text{Al}/^{27}\text{Al}$ distribution observed in CAIs would require that supernovae of a given mass formed at just the right time before solar system formation so that their protoCAIs’ ^{26}Al had decayed to 5×10^{-5} of their ^{27}Al . For example, protoCAIs from the above-mentioned $15M_{\odot}$ supernova would have to have formed 620,000 years prior to ones from the $25M_{\odot}$ star, so that all ended up with $^{26}\text{Al}/^{27}\text{Al} \approx 5 \times 10^{-5}$. ProtoCAIs from other supernovae with different bulk $^{26}\text{Al}/^{27}\text{Al}$ would have to have formed at their own specific times. But supernovae are essentially stochastic events, so such a fine-tuning of when certain stellar explosions would occur is extraordinarily unlikely. When one considers that CAIs show evidence for other extinct radioactivities, also with relatively uniform abundances far below expectations for fresh supernova nucleosynthesis, it is

clear that CAIs cannot have formed as supernova condensates. Allowing significant isotopic exchange in the solar nebula only makes the situation more difficult, since this would require even more fine tuning, where each individual CAI would have to be processed just the exact amount needed to result in a composition similar to every other inclusion.

4. Supernova Mixing

The above isotopic arguments mainly considered the bulk isotopic yields of supernova ejecta because Cameron's model for CAI formation assumes that supernova ejecta are very well homogenized. This assumption is based on recent simulations of Type II supernova explosions (Kifonidis et al. 2003) that suggest that hydrodynamical instabilities can lead to a very high degree of mixing throughout the supernova envelope. However, even state-of-the-art hydrodynamical calculations of supernovae are highly simplified (e.g., 2-dimensional) and include large numbers of assumptions and relatively unconstrained parameters. At the same time, the launch of the *Chandra* x-ray observatory has made it possible to study the distribution of elements in real supernova remnants with unprecedented resolution. Observations of several such remnants indicate that supernovae are not homogenized at all. For example, *Chandra* x-ray images of the famous Cassiopeia-A supernova remnant have revealed distinct clumps and jets of Fe, Si, and other elements synthesized in the supernova (Hughes et al. 2000). Hydrodynamic effects during the explosion have apparently led to overturn of material in the ejecta, but not homogenization. Another remnant, G292.0+1.8, has ejecta enriched in O, Ne and Mg, and little evidence for explosive nucleosynthesis products or for mixing (Park et al. 2004). Remnant N49B has ejecta enriched in Mg and Si, but again no evidence for mixing of heavier elements (Park et al. 2003).

Additional evidence that supernova ejecta are heterogeneously mixed and isotopically diverse comes from meteoritic presolar grains from supernovae (Amari & Zinner 1997; Clayton & Nittler 2004). These grains of SiC and graphite are known to originate in supernovae due to the inferred presence of ^{44}Ti , a supernova-synthesized radioactive isotope with a half-life of fifty years (Nittler et al. 1996). The isotopic compositions of these grains span huge ranges for some elements (e.g., $^{12}\text{C}/^{13}\text{C}=5-10,000$) and indicate mixing of different supernova regions without complete homogenization (Hoppe et al. 2000; Travaglio et al. 1999).

Thus, rather than indicating well-mixed and homogenized ejecta, astronomical observations and presolar grain studies show that supernovae are heterogeneously mixed and highly diverse. This only makes it more difficult to explain the relatively uniform and near-solar isotopic compositions of CAIs if the inclusions formed originally in supernovae. For example, the range of O isotopic ratios expected from different supernovae would be far higher than indicated by Figure 1 if the compositions of individual supernova regions were included. Even supernovae of the same mass could be expected to produce highly isotopically diverse materials if the degree of mixing is different in each.

5. A Single Supernova?

In the preceding sections, I demonstrated that the isotopic uniformity of CAIs almost certainly precludes an origin for them in multiple supernova explosions, as suggested

by Cameron (this volume), since different supernovae have highly diverse and anomalous isotopic compositions. But what about a single supernova, as first suggested by Cameron (2003)? Formation of CAIs as pristine condensates from any single supernova is completely precluded by the O isotopic evidence discussed above. Condensation as protoCAIs in a single presolar supernovae followed by remelting in the solar nebula could be consistent with the O isotopic observations, if the supernova ejecta from which the protoCAIs condensed had O isotopic ratios along the CAI mixing line (e.g., $>25M_{\odot}$ for bulk ejecta, Figure 1). However, it is far from clear that such a scenario could be made consistent with all of the isotopic data for CAIs, especially for radioactive isotopes.

Supernovae have bulk $^{26}\text{Al}/^{27}\text{Al}$ ratios much higher than the canonical CAI value of 5×10^{-5} (Section 3). Thus, either the single supernova source must have occurred long enough (~ 4 million years) before solar system formation such that its ^{26}Al had decayed sufficiently, or the lower CAI ^{26}Al abundance would have to arise from isotopic exchange with nebular gas during the melting event(s). The former situation is highly unlikely because with time, ejecta from individual supernovae are gradually diluted in the interstellar medium with preexisting material and the ejecta of subsequent stars. It is much more plausible to preferentially have material from a single supernova if the supernova occurred very close in time and space to the formation of the Solar System, perhaps even triggering solar system collapse (Cameron 2003). As discussed above, however, requiring dilution of isotopic signatures by exchange in the nebula has the difficulty of explaining the uniformity of isotopic compositions, since each CAI, presumably melting and interacting with the nebula as an individual object, would have to undergo just the right amount of exchange to end up with basically the same composition as every other CAI, for many different elements. Moreover, simple mixing calculations indicate that sufficient isotopic exchange to explain a 5% ^{16}O enrichment of the final CAI would still result in a $^{26}\text{Al}/^{27}\text{Al}$ ratio much higher than the canonical value (Figure 3). In addition, the isotopic signatures of other isotopically anomalous elements in CAIs are not those of bulk supernova ejecta, but rather specific nucleosynthetic processes (Meyer, Krishnan, & Clayton 1996).

Note that these arguments do not preclude either that the ^{26}Al observed in CAIs formed in a single supernova or that the solar system formation itself was triggered by shock waves from one or more supernova explosions. However, if the ^{26}Al was injected by a supernova, it is clear that it was not carried by the same objects that we recognize today as CAIs.

6. Conclusions

The isotopic composition of the Solar System is the result of mixing of the ejecta of an enormous number of stars over the age of the Galaxy. Supernovae are expected to have highly heterogeneous elemental and isotopic compositions, both between different regions of an individual supernova, and between different supernovae. Such expectations are supported by modern theories of stellar evolution and nucleosynthesis and borne out by observations of supernovae, their remnants, and meteoritic grains that formed in presolar supernovae. The high degree of isotopic uniformity of CAIs and the close similarity of their compositions (within 10%) to the solar composition

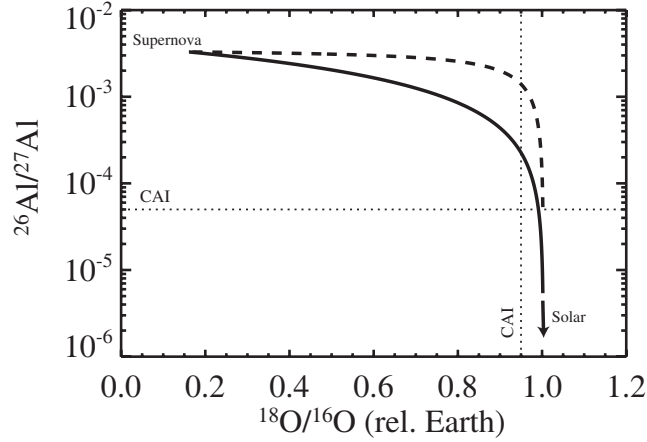


Figure 3. Results of a simple mixing calculation between a $25 M_{\odot}$ supernova (Rauscher et al. 2002) and the assumed composition of the solar nebula ($^{26}\text{Al}=0$; $^{18}\text{O}/^{16}\text{O}=\text{terrestrial}$). This model assumes that the supernova occurred shortly before solar system formation so that no ^{26}Al is lost to radioactive decay. The solid curve indicates the most conservative case, where it is assumed that the CAIs have solar elemental abundances. For this case, sufficient mixing to reproduce the 5% ^{16}O excess of CAIs results in $^{26}\text{Al}/^{27}\text{Al}=2\times 10^{-4}$, 40 times higher than observed in CAIs. The long-dashed line indicates the more realistic case that Al is enriched by a factor of ten in CAIs; in this case $^{26}\text{Al}/^{27}\text{Al}>10^{-3}$ when $^{18}\text{O}/^{16}\text{O}$ matches the CAI composition.

(assumed to be \sim terrestrial) rule out the possibility that these interesting objects formed as pristine supernova condensates. It cannot be unequivocally ruled out that CAIs formed as supernova condensates with highly unusual isotopic compositions and these compositions got mostly erased by processing in the early Solar System. However, in this scenario, the initial population of protoCAIs would have had a highly diverse range of compositions. Thus, in the solar nebula each individual CAI would have had to somehow “know” how many atoms of each element to exchange such that its final isotopic composition matched that of all the other inclusions. Occam’s razor indicates that we accept the much simpler and more likely explanation for the uniformity of CAI isotopic compositions: that the CAIs formed from a relatively well-homogenized reservoir of \sim solar composition, the solar nebula itself. The small isotopic anomalies that are observed in CAIs clearly represent in some cases a remnant of presolar supernova nucleosynthesis, but the inclusions themselves did not form in supernovae.

Acknowledgments. This paper was written at the urging of Sasha Krot and Gary Huss. It was improved by reviews by Yunbin Guan and Gary Huss, for which the author is grateful.

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