LOW-^{26}AL/^{27}AL CORUNDUM-HIBONITE INCLUSIONS (LAACHIs): HOW TO MAKE INCLUSIONS WITHOUT ^{26}AL IN A SOLAR NEBULA FULL OF IT.

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Introduction: The solar nebula contained the short-lived radionuclide ^{26}Al ($t_{1/2}$ =0.72 Myr), and most calcium-rich, aluminum-rich inclusions (CAIs) formed with initial ratios $(^{26}\text{Al}/^{27}\text{Al})_0 \approx 5 \times 10^{-5}$ [1]. An enduring mystery is whether that ^{26}Al was inherited from the molecular cloud, in which case it would have been distributed homogeneously in the solar nebula. If it was, then variations in $(^{26}\text{Al}/^{27}\text{Al})_0$ ratios can be interpreted as differences in formation times, and the ^{26}Al-^{26}Mg system would be a valid chronometer. Alternatively, it may have been injected into the disk at some point, and then homogenized in the disk.

Two types of heterogeneities are recognized. Mismatches between Al-Mg and Pb-Pb ages have been interpreted as CAIs forming in a region with twice the ^{26}Al as the regions forming chondrules and most meteoritic material [2,3]. We interpret the data instead as CAIs forming in a nebula with homogeneous ^{26}Al and subsequently being reset for Pb-Pb but not Al-Mg ages, during the chondrule-forming epoch [4,5]. The toher type of heterogeneity is CAIs with remarkably low $(^{26}\text{Al}/^{27}\text{Al})_0$ ratios that can't be interpreted as resetting; they have been interpreted as forming before the solar nebula contained ^{26}Al [6,7], in which case the ^{26}Al-^{26}Mg system would not be a valid chronometer.

The inclusions with very low $(^{26}\text{Al}/^{27}\text{Al})_0$ include some FUN (Fractionations and Unknown Nuclear Effects) CAIs, corundum grains, PLACs (PLAty Crystals of hibonite), grossite-bearing CAIs, and other hibonite ±corundum-bearing inclusions. Most are found in carbonaceous chondrites such as Allende that accreted no later than 3 Myr after most (normal) CAIs [8]. If formed with the canonical 5×10^{-5} ratio, these must have $(^{26}\text{Al}/^{27}\text{Al})_0 > 3 \times 10^{-6}$; yet some of these CAIs record $(^{26}\text{Al}/^{27}\text{Al})_0 < 10^{-7}$. They have been interpreted as forming before "injection" of ^{26}Al i.nto the solar nebula, which originally contained almost no ^{26}Al [7].

LAACHIs: We re-examine which inclusions are truly characterized by low $(^{26}\text{Al}/^{27}\text{Al})_0$ ratios. Few of the 28 known FUN CAIs formed without ^{26}Al: as reviewed by [9], only four definitively did not; all are dominated by hibonite. Five FUN CAIs do not contain hibonite; all have $(^{26}\text{Al}/^{27}\text{Al})_0 > 3 \times 10^{-6}$ and could have been reset in the solar nebula. This strongly suggests the ^{26}Al heterogeneity is associated with hibonite, and is therefore chemical rather than spatial or temporal. In **Figure 1** we plot the distribution of $(^{26}\text{Al}/^{27}\text{Al})_0$ ratios of different types of inclusions in The modal values are low in corundum grains (0×10^{-6}), hibonite-rich FUN CAIs (2×10^{-6}), and PLACs (2×10^{-6}), and are typically low in other hibonite- or corundum-dominated inclusions and grossite-bearing CAIs [6,10]. In contrast, $(^{26}\text{Al}/^{27}\text{Al})_0$ is typically (4-5) × 10^{-5} in SHIBs (Spinel and HIBonite inclusions) and the much more common 'normal' CAIs (dominated by melilite, anorthite, etc.). So strong is the association of low $(^{26}\text{Al}/^{27}\text{Al})_0$ with the calcium aluminate phases of corundum [Al_2O_3], hibonite [$CaO{\bullet}6(Al_2O_3)$] and grossite [$CaO{\bullet}2(Al_2O_3)$], which are the most refractory phases, that we collectively call such objects "Low-^{26}Al/^{27}Al Corundum-Hibonite Inclusions", or "LAACHIs". The modal abundance of 180 LAACHIs is $(^{26}\text{Al}/^{27}\text{Al})_0 \approx 1 \times 10^{-7}$, and the most ^{26}Al-deficient objects include the FUN CAI *HAL*, with $(^{26}\text{Al}/^{27}\text{Al})_0 < 5 \times 10^{-8}$ [11].

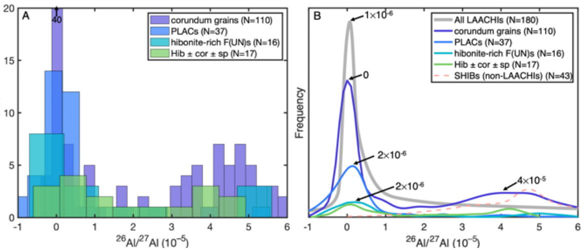

Figure 1: $(^{26}\text{Al}/^{27}\text{Al})_0$ ratios of various inclusions, showing correlation between low $(^{26}\text{Al}/^{27}\text{Al})_0$ and dominance by corundum or hibonite (in contrast to SHIBs and normal CAIs). We call such objects LAACHIs.

Astrophysical Model: The identification of LAACHIs as a distinct class of object allows us to explain the heterogeneity of ^{6}Al. We present a model for how low-^{26}Al/^{27}Al inclusions could form in a solar nebula that inherited ^{26}Al from the molecular cloud and had uniform $^{26}\text{Al}/^{27}\text{Al} \approx 5 \times 10^{-5}$ from its beginning. In the earliest (< 10^5 yr), hottest (> 1350 K) regions of the solar nebula, the solids that would exist and coagulate into larger particles would be refractory—not because they condense first in a cooling nebula (from gas with the average ^{26}Al/^{27}Al), but because they evaporate last as the solar nebula heats up, meaning solids retain characteristics of presolar grains, as suggested by [12].

^{26}Al is very heterogeneously distributed among presolar grains. Most solar system Al likely derived from, of spinel [$MgAl_2O_4$], corundum or hibonite grains 0.5-2 μm in size, as well as Al in silicate grains, from asymptotic giant branch (AGB) stars, > 20 Myr before the Sun's formation; they contained no live ^{26}Al. Live ^{26}Al would have been in grains solely from recent (< 20 Myr), nearby (few pc) supernovae or Wolf-Rayet ejecta, typically smaller (< 50 nm) grains of similar refractory minerals. Nanospinels are small (< 50 nm) presolar grains of chromium spinel [$Mg(Al,Cr)_2O_4$] that are the carriers of ε^{54}Cr anomalies [13] and have been suggested (based on ^{26}Mg excesses) as the carriers of ^{26}Al [14]. We hypothesize all ^{26}Al in the solar nebula was contained in these or similar grains.

Conditions in the solar nebula likely resembled those calculated by [15]: at ≈0.6 AU and ≈0.1 Myr, when the Sun still had mass 0.36 $M_\odot$, surface densities were 1.25×10^4 g cm^{-2}, turbulence parameter $\alpha \sim 10^{-3}$, pressures 3×10^{-4} bar, and temperatures 1425 K. As presolar grains were advected into this region, most vaporized; spinel would lose Mg and Cr, becoming corundum; corundum would react with Ca vapor to form hibonite or grossite; these grains, plus much rarer perovskite [$CaTiO_3$] grains, would be the only solids, and they would coagulate to form larger aggregates.

Notably, these grains would be presolar in many respects, but would reflect the oxygen isotopic composition of the solar nebula. Using standard diffusion coefficients [15], at 1400 K > 99% of oxygen atoms are exchanged with the gas in ~10^3 years, comparable to or shorter than their residence time in the hot region.

These grains would be charged, with adsorption of electrons balancing thermionic emission of electrons at rates depending on the work functions W of the grain materials [16]. Corundum and hibonite have W ≈ 4.7 eV and would have charges ≈ $(-240e)\,a$, where a is the grain radius in μm. Perovskite grains have W ≈ 3.0 eV and charges ≈ $(+400e)\,a$. For a small hibonite/corundum grain (a_2) to approach a large hibonite/corundum grain (a_1), they must have relative velocity > $6/a_2$ cm s^{-1}, but their relative velocities due to turbulence are ≈ $4\,(a_1\text{-}a_2)$ cm s^{-1} [9]. The net effect is that *only* the larger, ^{26}Al-free grains several microns in size can coagulate with each other and grow into larger objects. They can reach 100 μm sizes in 10^2-10^3 yr before diffusing out of the region.Throughout that growth, the submicron, ^{26}Al-bearing nanospinels would not be accreted, despite being in the same environment.

The coagulation of corundum grains and reaction with Ca vapor to produce hibonite, would naturally explain the morphologies of cordundum grain aggregates, PLACs, corundum-hibonite inclusions, etc., as well as their lack of ^{26}Al.

In cooler regions of the nebula, grains of spinel, silicate, etc., would be more common, and less charged, and nanospinels would be accreted more easily. Minerals formed in those cooler regions may have routinely contained live ^{26}Al. Inclusions formed from mixtures of these minerals could have contained live ^{26}Al. Normal CAIs, dominated by melilite, anorthite, etc., could have formed with the canonical ratio. As mixtures of spinel and hibonite, SHIBs are not LAACHIs, and could have formed with slightly subcanonical $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0$.

Collateral Predictions: Our model makes testable predictions about LAACHIs (that are generally observed among PLACs, etc. [9]. First, despite forming in a hot region with the most refractory minerals, they should contain no refractory metal, as these also would be submicron and negatively charged.

LAACHIs should largely reflect a solar Mg isotopic composition, except that lacking contributions from supernova presolar grains, they may exhibit deficits δ^{26}Mg ≈ -3‰. Likewise, as they react with Ca in the gas phase, they should have near-solar Ca isotopic compositions. Al and ^{26}Al would not be exchanged, as we calculate 99.9999% of Al would be condensed at 1400 K.

We predict that LAACHIs formed with live ^{41}Ca and ^{10}Be. While the vast majority of CAIs formed with $(^{10}\mathrm{Be}/^{9}\mathrm{Be})_0 \approx 7.1 \times 10^{-4}$ [18], the hibonite-dominated LAACHIs formed with $(^{10}\mathrm{Be}/^{9}\mathrm{Be})_0 \approx 5.3 \times 10^{-4}$, consistent with most being thermally reset during the chondrule-forming epoch. Notably, the non-hibonite-bearing FUN CAIs *KT-1* and *CMS-1* are consistent in their Al-Mg and Be-B systematics with forming or resetting at 0.8 Myr [$(^{10}\mathrm{Be}/^{9}\mathrm{Be})_0 \approx 4 \times 10^{-4}$]. More statistics of $(^{10}\mathrm{Be}/^{9}\mathrm{Be})_0$ in LAACHIs will test these predictions.

Conclusions: It is possible to form certain inclusions, dominated in corundum or hibonite (or grossite), without ^{26}Al, despite forming in a solar nebula with canonical $^{26}\mathrm{Al}/^{27}\mathrm{Al} \approx 5 \times 10^{-5}$. Collateral evidence supports this origin for LAACHIs. This removes demand for "late injection" scenarios [e.g., 7].

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