

## Presolar Stardust In The Solar System: Recent Advances for Nuclear Astrophysics

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**Larry R. Nittler\***

*Dept. of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Rd NW,  
Washington DC, 20015, USA*

*E-mail: lnittler@ciw.edu*

Grains of presolar stardust are identified in extraterrestrial materials on the basis of highly anomalous isotopic compositions. These compositions reflect those of the stellar gases from which they condensed more than 4.5 billion years ago and serve as detailed probes of nuclear processes in space including Galactic chemical evolution, nucleosynthesis and mixing processes in stars. A large number of presolar phases have now been identified, including various oxides, silicates, carbides and elemental carbon, with apparent origins in red giants, asymptotic giant branch stars, supernovae and perhaps novae. This paper provides some illustrative examples of how presolar stardust provides new insights for nuclear astrophysics.

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\*Speaker.

## 1. Introduction

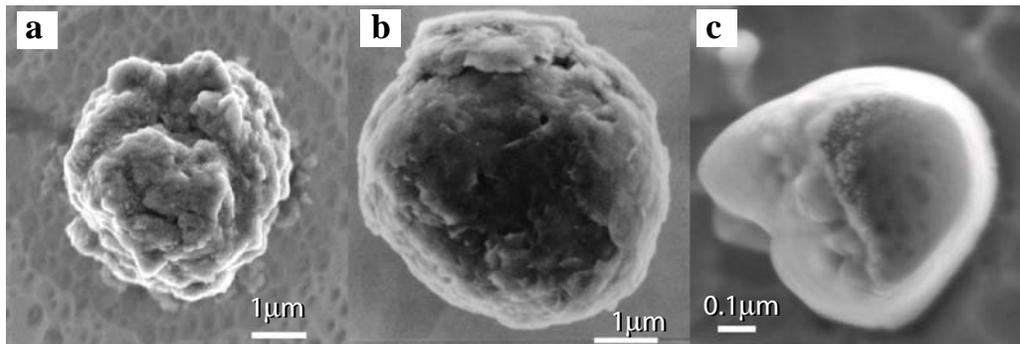
Presolar stardust grains are tiny dust specks that condensed in outflows and explosions of previous generations of stars and survived processing in the interstellar medium and early Solar System [1, 2, 3]. They comprise a minor portion (<ppb to a few hundred ppm) of primitive meteorites and interplanetary dust particles (microscopic extraterrestrial samples collected in the stratosphere). They were discovered in 1987, following a long search for carriers of isotopically anomalous noble gases in meteorites. Because they escaped homogenization processes in the early solar system, they are identified by their highly unusual isotopic compositions, relative to all other materials in the solar system. These compositions reflect both Galactic chemical evolution (GCE) and nuclear processing in the parent stars. Because the presolar grains can be studied in great detail in modern microanalytical laboratories, they can provide high-precision constraints on nuclear astrophysics, complementary to traditional astronomical observations.

Each presolar grain is a sample of a *specific* place in a *specific* star at a *specific* time, with very little or no processing since its formation. Presolar stardust can thus provide important information about a range of astrophysical processes. In particular, the ability to precisely determine the isotopic composition of multiple elements in a single presolar grain places unprecedented quantitative constraints on stellar evolution and nucleosynthesis models (e.g. [4]). Mineralogical and microstructural studies provide detailed information on grain formation processes in stars (e.g., [5, 6]). A detailed review of presolar grains and their applications in astrophysics and space science is beyond the scope of this paper. Here I will focus on some examples and recent advances to illustrate how meteoritic stardust provides new insights and quantitative constraints on nuclear processes in the galaxy. The interested reader is referred to longer reviews (e.g., [1, 2, 3]) and the current literature for additional information.

## 2. Analysis and Types of Presolar Grains

The discovery and increasingly detailed characterization of presolar grains has been made possible by technological advances in micro- and nano-analytical instrumentation. For example, modern secondary ion mass spectrometers (SIMS) can determine, with high sensitivity, isotopic ratios of many elements in sub-micrometer solid samples, allowing for identification of presolar grains with astrophysically relevant sizes [7, 8, 9]. Once identified, a presolar grain can be further analyzed by a range of techniques. For example, additional isotopic signatures might be determined using SIMS, noble-gas mass spectrometry [10], or resonance ionization mass spectrometry (RIMS, [11, 12]). Detailed chemical and mineralogical investigations can be carried out by scanning and transmission electron microscopy and/or Auger spectroscopy (e.g., [5, 13, 6, 14]).

Example images of a few of the known types of presolar grains are shown in Fig. 1; some basic information for the known presolar phases are summarized in Table 1. Most of the carbonaceous grains (and  $\text{Si}_3\text{N}_4$ ) have been identified in acid residues of meteorites from which the dominant phases (silicates, metal, sulfides) have been removed. O-rich phases have been identified primarily by automated techniques originally in acid residues [15, 16], but now also *in situ* [7, 8, 9] via isotopic imaging. Some phases (refractory carbides, metal) have been identified as sub-grains within larger presolar graphite grains [5, 13, 17]. Note that although several hundred



**Figure 1:** Electron micrographs of presolar grains: a) SiC; b) Graphite; c) Al<sub>2</sub>O<sub>3</sub>; Based on [3].

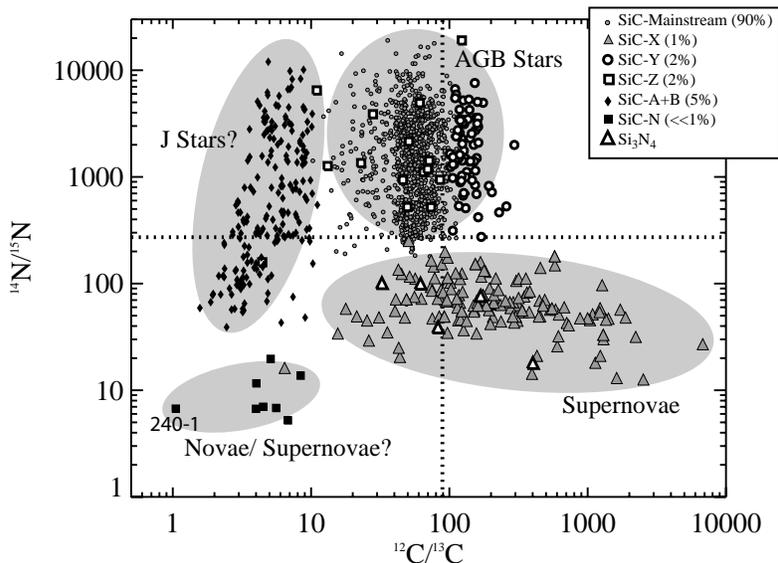
**Table 1:** Types of presolar grains in meteorites and interplanetary dust particles (IDPs), after [2]. AGB=Asymptotic Giant Branch stars, SNe=Supernovae, RG=Red Giant stars.

Phase	Abundance (ppm)	Size	Source(s)
Nanodiamond	1400	2 nm	SNe(?)
Silicates (olivine, pyroxene, Ca-, Al-rich, glass ...)	≈500 (IDPs) ≈100 (meteorites)	0.1–1 μm	AGB, SNe
SiC	10	0.1–20 μm	AGB, SNe, J-stars, novae(?)
Graphite	1–2	1–20 μm	AGB, SNe
TiC, ZrC, MoC, RuC, FeC, Fe-Ni	(sub-grains in graphite)	5–220 nm	AGB, SNe
Silicon Nitride (Si <sub>3</sub> N <sub>4</sub> )	>0.002	~1 μm	SNe
Oxides (Al <sub>2</sub> O <sub>3</sub> , MgAl <sub>2</sub> O <sub>4</sub> , CaAl <sub>12</sub> O <sub>19</sub> , TiO <sub>2</sub> , (Mg,Fe)Cr <sub>2</sub> O <sub>4</sub> )	>10	0.1–3 μm	RG, AGB, SNe

presolar silicate grains have now been identified, very few have had detailed mineralogical identifications. Chemical analysis indicates a wide range of silicate compositions. Moreover, more than half that have been analyzed by transmission electron microscopy have proven to be amorphous, non-stoichiometric phases. Note also that the origin for the meteoritic nanodiamonds is unsettled; a solar system origin for most of the diamonds cannot be excluded [18].

### 3. Implications for Nuclear Astrophysics

Because the parent stars of presolar grains ended their lives more than 4.5 Gyr ago, one must use an iterative approach to identify the type of star that produced any given grain. For example, Fig. 2 shows the distributions of C and N isotopic ratios measured in presolar SiC grains. The data fall into distinct groupings. Comparison with spectroscopic observations and theoretical models indicates that these families represent different types of stellar sources, as indicated on the Figure. For example, the C isotopic distribution of the dominant “Mainstream” population is remarkably similar to that observed in C-rich asymptotic giant branch (AGB) stars [19], pointing to these as sources. Many other isotope signatures in the grains point to an AGB source as well and the high-precision data obtainable on the grains can thus be used to constrain AGB models. Similarly, the “X-grains” have signatures pointing to an origin in Type II supernovae and can provide unique information about such explosions of massive stars. Analogous groupings of O isotopic ratios of



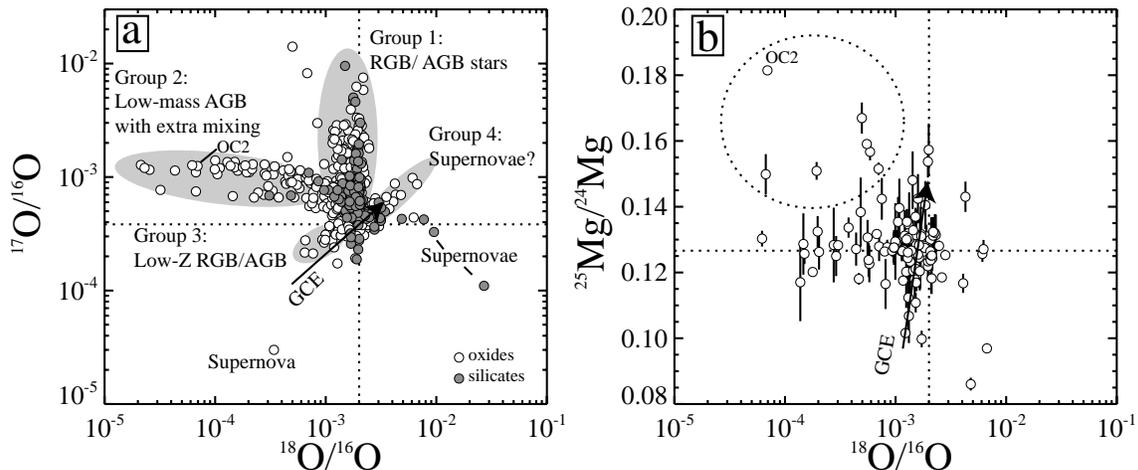
**Figure 2:** C and N isotopic ratios measured in individual presolar SiC grains (see [2] for data sources). Different groupings of isotopic compositions can be attributed to different stellar sources, as indicated. Grain 240-1 [20] is the best candidate yet identified for a nova condensate. Dotted lines indicate solar ratios in this and subsequent figures.

presolar oxide and silicate grains have been used to identify red giants, AGB stars and SNe as the sources of these (Fig. 3).

### 3.1 Grains from Low-mass Stars

It is now well accepted that most SiC grains originated in low-mass ( $<2M_{\odot}$ ) AGB stars: the mainstream grains from roughly solar-metallicity stars, and the rare Y and Z grains from lower-metallicity stars. Among the strongest pieces of evidence for this comes from the isotopic composition of heavy trace elements in single grains, made possible by resonance ionization mass spectrometry (RIMS). RIMS measurements have revealed almost-pure *s*-process isotopic signatures of many elements, including Mo, Zr, Sr, Ba, and Ru (*e.g.*, [4]). In fact, the relatively high precision of the measurements provides for quantitative constraints on *s*-process models. For example, a recent comparison of models with data acquired for multiple elements in single SiC grains [21] constrains the amount of  $^{13}\text{C}$  present in the region between the AGB He- and H-burning shells, a free parameter in AGB nucleosynthesis calculations [22, 4], to a narrow range around that required to explain the solar *s*-process abundance distribution. Moreover, deviations between model trends and SiC trace-element data have pointed both to the original presence of radioactive elements [12] and to incorrect neutron-capture cross-sections [23, 24].

Most presolar O-rich grains (Group 1, Fig. 3a) are enriched in  $^{17}\text{O}$  and slightly depleted in  $^{18}\text{O}$ , relative to solar composition. Their compositions are well-explained by models of dredge-up in low-mass red giant stars, provided they formed from stars with a range of masses and metallicities [15]. The O isotope distribution of these and the Group 3 grains strongly indicates the existence of an age-metallicity relation in the presolar solar neighborhood of the Galaxy. Initial  $^{26}\text{Al}/^{27}\text{Al}$  and



**Figure 3:** O isotopic ratios measured in individual presolar oxide and silicate grains (see [2, 16] for data sources). Different grain Groups and individual grains can be attributed to different stellar sources, as indicated. Arrows indicate rough trends expected for GCE of isotopic ratios; dotted ellipse in (b) indicates unusually  $^{25}\text{Mg}$ -rich and  $^{18}\text{O}$ -poor grains.

$^{41}\text{Ca}/^{40}\text{Ca}$  ratios, inferred for many of the grains from excesses in radioactive daughter products, are in good agreement with predictions for low-mass AGB stars [16]. The more  $^{18}\text{O}$ -depleted Group 2 grains likely formed in low-mass AGB stars experiencing “extra” mixing, not predicted by standard 1-d models of stellar evolution. Extra mixing is also indicated by high inferred initial  $^{26}\text{Al}/^{27}\text{Al}$  ratios in the Group 2 grains as well as by some C and N isotopic compositions of presolar SiC grains [25, 26, 27]. The physical mechanism of the mixing (often called “cool bottom processing” or CBP, [28]) is unknown, but may be related to shear instabilities, thermohaline instabilities and/or magnetic effects [29, 30, 31]. The high-precision grain data can help constrain parameters of mixing models, for example the mixing rate and temperature reached by circulating material [26]. Interestingly, the mixing parameters required to explain the SiC data and the oxide data appear to be quite different, indicating that CBP operates differently in O-rich versus C-rich AGB stars.

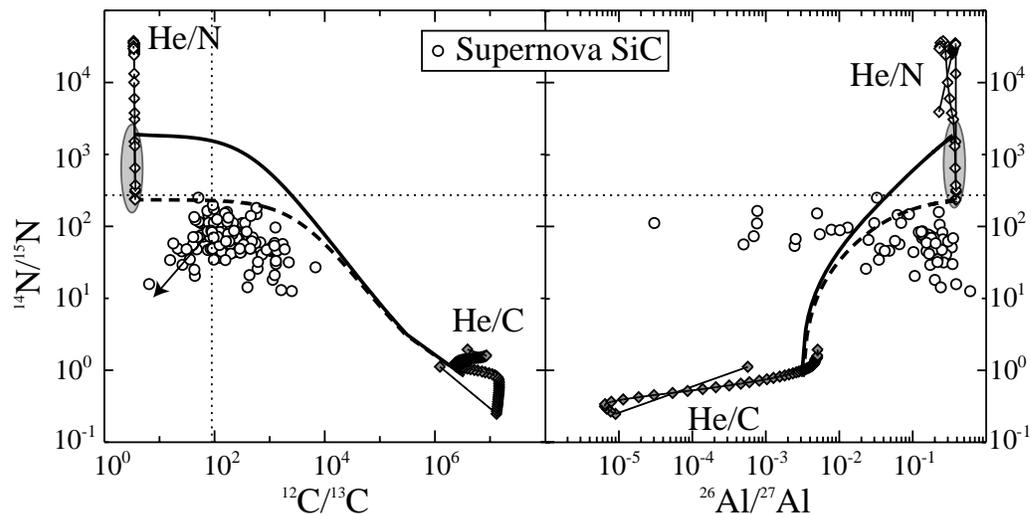
Mg isotopes are affected by both GCE [32] and nuclear processing in stars [33] and Mg is one of the few elements amenable to spectroscopic isotopic analysis in stars [34]. Recent high-precision Mg isotopic data for presolar oxide grains (Fig. 3b) are thus valuable for comparisons with observations and model predictions [35, 36, 16]. Group 1 grains show evidence for the expected increase in  $^{25}\text{Mg}/^{24}\text{Mg}$  with metallicity due to GCE, though there is considerable scatter. Several  $^{18}\text{O}$ -depleted Group 2 grains show relatively large excesses in  $^{25}\text{Mg}$  (dotted ellipse in Fig. 3b), comparable to those predicted for intermediate-mass AGB (IM-AGB) stars. However, the O isotopic ratios of these grains indicate lower mass stellar parents, which are not predicted to have such  $^{25}\text{Mg}$  excesses. An IM-AGB origin suggested for the extreme grain OC2 [36] has also been ruled out by recent re-evaluation of the  $^{16}\text{O}(p,\gamma)^{17}\text{F}$  reaction rate [37]. The unusual  $^{25}\text{Mg}$  excesses observed in these grains as well as many main-sequence stars might indicate strongly heterogeneous GCE of Mg isotopes or perhaps mass-transfer from IM-AGB companions to lower-mass stars in binary systems [16].

### 3.2 Grains from Supernovae and Novae

A small fraction of presolar SiC (“X grains”), the very rare Si<sub>3</sub>N<sub>4</sub> grains and a larger fraction of presolar graphite grains are believed to originate in the cooling ejecta of Type II supernovae (SN). The strongest evidence for a SN origin is the observation of large <sup>44</sup>Ca excesses, unaccompanied by anomalies in other stable Ca isotopes, in many grains [38, 39]. This signature points to *in situ* decay of <sup>44</sup>Ti, which has a half-life of  $\approx 60$  y and is produced solely in SN. Moreover, extinct <sup>49</sup>V observed in some grains [40] also indicates a supernova origin and requires that they formed within one year of the parental explosions. A large number of additional isotope signatures observed in the grains also point to a SN origin. A key observation of the supernova grain data is the apparent necessity to heterogeneously mix material from different zones in order to quantitatively reproduce grain isotopic compositions using detailed SN nucleosynthesis calculations [39, 41, 42]. Although extensive macroscopic mixing is both observed in and predicted for SN ejecta, the detailed microscopic mixing required by the grains poses challenges to our understanding of SNe (*e.g.*, [43]).

Isotopic data for the SN grains have both provided important insights into supernova nucleosynthesis and raised important puzzles. For example, the isotopic patterns observed for heavy elements Mo, Zr, Sr, Ba and Fe in SiC X grains are completely distinct from those observed in the AGB grains, and also differ from expectations for *r*- or *p*-processes associated with supernovae. Rather, these point to a “neutron-burst” nuclear process occurring in a massive star’s He shell during the explosion [44]. A key unsolved problem is the fact that the grains are uniformly more <sup>15</sup>N-rich than can be explained by SN mixing models (Fig. 4). Qualitatively, the data point to mixing of the He- and C-rich layer (enriched in <sup>12</sup>C and <sup>15</sup>N) and the overlying He/N zone, to explain high <sup>26</sup>Al/<sup>27</sup>Al ratios. However, the extremely high abundance of <sup>14</sup>N in the He/N zone has precluded quantitative matching of the data (mixing curves in Fig. 4). The problem is exacerbated by the recent identification of supernova SiC and graphite grains with very low <sup>12</sup>C/<sup>13</sup>C ratios ( $\lesssim 10$ , [45, 46]); these data point to the existence a SN reservoir enriched in <sup>13</sup>C, <sup>15</sup>N and <sup>26</sup>Al. Such a reservoir is hinted at in the most recent SN models of Heger and colleagues (A. Heger, pers. comm.). In their models of stars of mass  $\approx 25\text{--}30 M_{\odot}$ , a small region of the He/N zone is enriched in <sup>15</sup>N, relative to the zone as a whole (grey ellipses in fig. 4). The nucleosynthetic origin of this <sup>15</sup>N “spike” is as-yet unresolved, but may be due to hot CNO burning during the SN explosion. In any case, even this new region is not sufficiently rich in <sup>15</sup>N to explain the data (dashed mixing curves in Fig. 4) but it points in the right direction. An alternative explanation, extensive production of <sup>15</sup>N during core He-burning in rotating massive stars [47], deserves further investigation as well. Finally, unusual Fe, Ni, Ca and Ti isotopic compositions were recently reported in presolar SN grains [46, 48]. It remains to be seen whether these can be adequately explained by nucleosynthesis models or if they will point to new insights about massive star evolution.

A small fraction of presolar oxide and silicate grains also likely formed in SNe (Fig. 3a). Interestingly, although the most abundant product of Type II SNe is <sup>16</sup>O, only one <sup>16</sup>O-rich SN grain has been found [49]. The remainder of O-rich grains believed to have a SN origin are <sup>18</sup>O-rich [50, 16], reflecting a contribution from the He-burning zone of the massive star. A SN origin for many of these grains is supported by <sup>25</sup>Mg depletions, due to partial mixing of <sup>24</sup>Mg-rich material from the inner parts of the parent SN (Fig. 3b, [16]). That a majority of presolar SN O-rich grains



**Figure 4:** Isotopic ratios measured in individual presolar SiC X-grains from supernovae compared with predicted compositions of two zones of a  $25M_{\odot}$  supernova (diamonds, Heger & Woosley, pers. comm.). A  $^{15}\text{N}$  rich sub-region of the He/N zone, not seen in previous SN calculations, is indicated by grey ellipses. Solid curves indicate mixing between the average compositions of He/N and He/C zones; dashed curves indicate mixing between the He/C zone and the most  $^{15}\text{N}$ -rich sub-region of He/N zone. Arrow in left panel indicates data trend towards highly  $^{13}\text{C}$ - and  $^{15}\text{N}$ -rich composition.

are apparently from outer layers of the parent stars might reflect preferential destruction of dust grains in deeper layers by reverse shocks [51].

Amari et al. [52] proposed a nova origin for a handful of isotopically unusual SiC and graphite grains, based mostly on very low  $^{12}\text{C}/^{13}\text{C}$  and  $^{14}\text{N}/^{15}\text{N}$  ratios (Fig. 2), but also on  $^{30}\text{Si}$  enrichments. However, a nova origin for these grains is somewhat problematic because the pure nova nucleosynthetic signatures must be greatly diluted to explain the data. Moreover, the identification of a supernova SiC grain with closely similar C and N isotopes [45] shows that SNe can produce compositions with lower  $^{12}\text{C}/^{13}\text{C}$  and  $^{14}\text{N}/^{15}\text{N}$  ratios than predicted and calls into question whether the other grains formed in novae or SNe. More recently, an Al-rich SiC grain was identified (240-1, Fig. 2, [20]) with  $^{12}\text{C}/^{13}\text{C}=1$ , low  $^{14}\text{N}/^{15}\text{N}$  and high inferred  $^{26}\text{Al}/^{27}\text{Al}$ . This grain's composition agrees well with nova models [53], without any dilution and is the strongest candidate found to date for a nova condensate in a meteorite.

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