Presolar Stardust in the Solar System: Implications for Nucleosynthesis and Galactic Chemical Evolution

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Abstract.
   Primitive meteorites and interplanetary dust particles contain presolar grains: pristine solid samples of stellar material. These grains of stardust are a new source of information on nuclear astrophysics, complementary to traditional astronomical observations. Identified phases include silicates, oxides, SiC, graphite (including sub-grains of metal and carbides), and silicon nitride. Most grains can be attributed to either asymptotic giant branch (AGB) stars or Type II supernovae, based on their isotopic compositions. Detailed high-precision isotopic data for the grains provide important and unique constraints on nuclear processes occurring in these stars.

INTRODUCTION

Presolar stardust grains are tiny mineral grains 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 are a trace component (<ppb to a few hundred ppm) of primitive meteorites and interplanetary dust particles (tiny extraterrestrial samples collected in the stratosphere). They were discovered in 1987, following a long search for carriers of isotopically anomalous noble gases in meteorites (see [4] for a historical review). 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.

   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. Fig. 1 shows secondary electron and oxygen isotopic ratio images, produced by a Cameca Instruments NanoSIMS 50L ion microprobe, of a small region of the primitive carbonaceous chondrite Alan Hills 77307. Most materials in the Solar System have highly uniform isotopic composition (<10% variation in O isotopes for instance) due to large-
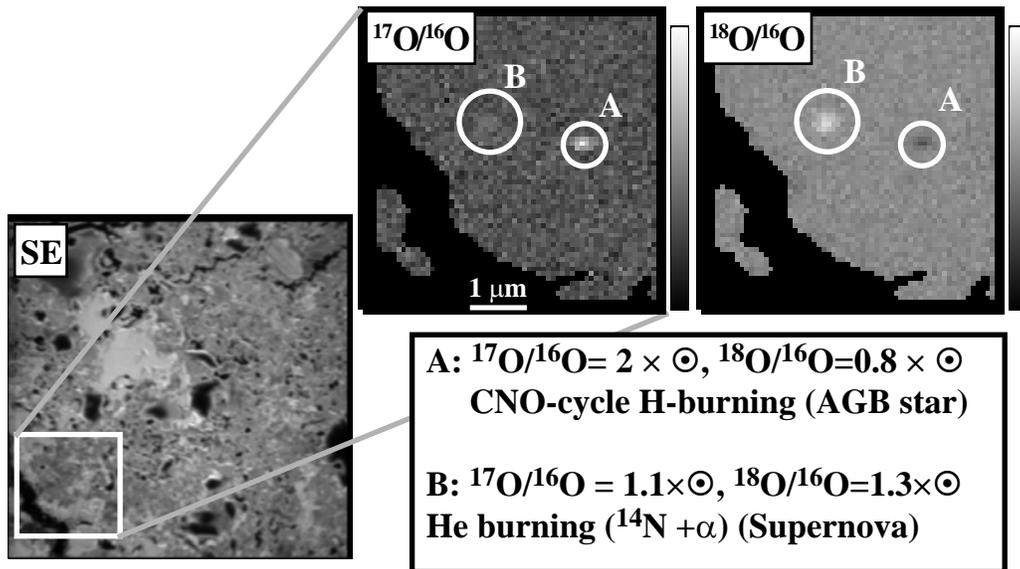
FIGURE 1. Scanning electron (SE) and O-isotopic ratio images of a small region of primitive meteorite ALHA 77307 (Nguyen and Nittler, unpub. data). Two grains (A and B, with indicated highly non-solar isotopic compositions) are identified as presolar silicate grains.

scale homogenization processes in the interstellar medium and early solar system and reflected in the homogeneous gray-scale of most pixels in the isotopic ratio images in Fig. 1. In contrast, two sub-μm grains in this region have relatively huge isotopic variations in both $^{17}O/^{16}O$ and $^{18}O/^{16}O$ ratios. These variations are much larger than can be explained by any known chemical fractionation process and point to nuclear reactions occurring in stars. Indeed, the isotopic patterns exhibited by the grains can be associated with specific nucleosynthetic processes, as indicated on the Figure.

Once identified as stardust, 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 [5], or resonance ionization mass spectrometry (RIMS, [6, 7]). Detailed chemical and mineralogical investigations can be carried out by scanning and transmission electron microscopy and/or Auger spectroscopy (e.g., [8, 9, 10, 11]). Because each 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 provides 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. [12]). Mineralogical and microstructural studies provide detailed information on grain formation processes in stars (e.g., [8, 13, 10]).

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 a few examples that illustrate how meteoritic stardust provides new insights and quantitative constraints on nuclear processes in the Galaxy. Several reviews of the field have been published in recent years [1, 2, 3] and the interested reader is referred to these and the current
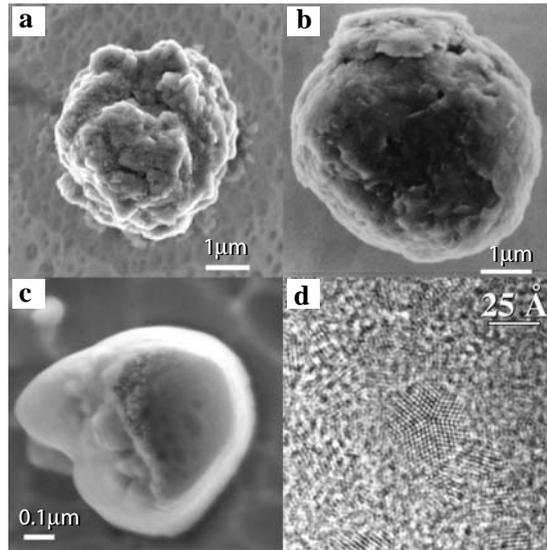
FIGURE 2. Electron micrographs of presolar grains: a) SiC; b) Graphite; c) Al_2O_3; d) nanodiamond. Reprinted from [3].

literature for additional information.

TYPES OF PRESOLAR GRAINS

A large number of presolar phases have now been identified (Table 1); example micrographs of a few are shown in Fig. 2. Most of the carbonaceous grains (and Si_3N_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 both *in situ* [14, 15, 16] and in acid residues [17, 18]. Some phases (refractory carbides, metal) have been identified as sub-grains within larger presolar graphite grains [8, 9, 19]. Note that although several hundred 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; it is posible that only a tiny fraction are presoalr grains [20].

IMPLICATIONS FOR NUCLEOSYNTHESIS

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. 3 shows the C and N isotopic ratios of 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

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 ...)	$\approx$500 (IDPs) $\approx$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_3N_4)	>0.002	$\sim$1 μm	SNe
Oxides (Al_2O_3, $MgAl_2O_4$, $CaAl_{12}O_{19}$, TiO_2, $(Mg,Fe)Cr_2O_4$)	>10	0.1–3 μm	RG, AGB, SNe

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 [21], 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 presolar oxide and silicate grains have been used to identify red giants, AGB stars and SNe as the sources of these.

Low- and Intermediate-Mass Stars

There is now a large body of evidence that most SiC grains originated in low-mass ($<2M_\odot$) AGB stars: the mainstream grains from roughly solar-metallicity stars, the rare Y and Z grains from lower-metallicity stars. One of the strongest pieces of evidence for this comes from isotopic measurements of heavy trace elements in single grains, made possible by resonance ionization mass spectrometry (RIMS). RIMS measurements of single presolar SiC grains reveal almost-pure *s*-process isotopic signatures of many elements, including Mo, Zr, Sr, Ba, and Ru (*e.g.*, [12]). In fact, the relatively high precision of the measurements provides for quantitative constraints on *s*-process models. For example, a free parameter in AGB nucleosynthesis calculations [23, 12] is the amount of ^{13}C present in the region between the AGB He- and H-buring shells, since the primary source of neutrons for the *s*-process in low-mass AGB stars is the ^{13}C(α,n) reaction. A recent comparison of models with data acquired for multiple elements in single SiC grains [24] constrains this parameter to a narrow range around that required to explain the solar *s*-process abundance distribution.

Presolar grains also provide important new information about mixing processes in low-mass AGB stars. Spectroscopic observations indicate that an "extra" mixing process, not predicted by standard 1-d models of stellar evolution occurs in low-mass red
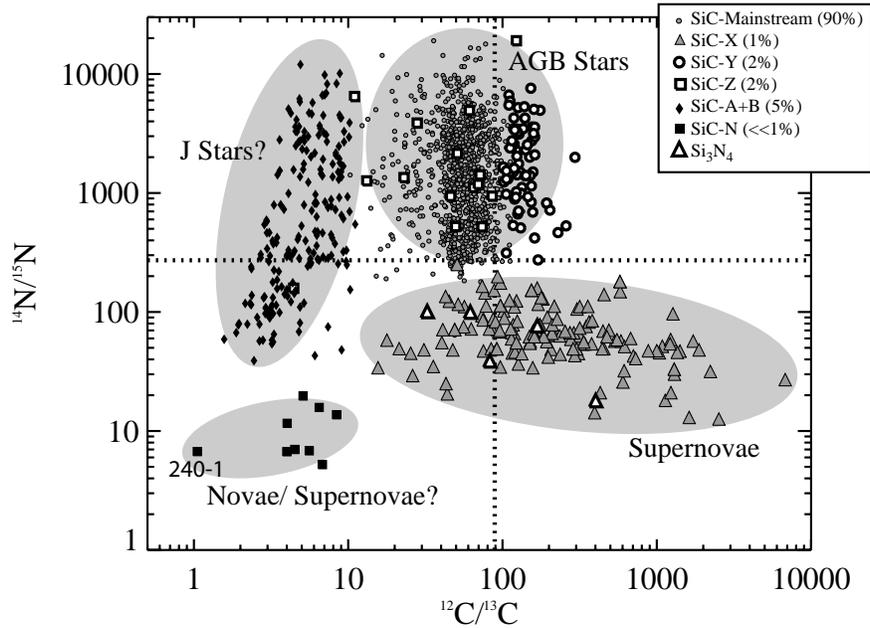
FIGURE 3. C and N isotopic ratios measured in individual presolar SiC grains (see [2] for data sources). Different groupings of isotopic compositions can be attributed to different stellar sources, as indicated. Grain 240-1 [22] is the best candidate yet identified for a nova condensate.

giants [25]. C and N isotopic ratios in presolar SiC grains [26, 27, 28] and O isotopes and inferred $^{26}Al/^{27}Al$ ratios in many presolar oxide grains [17] point to a similar process occurring in AGB stars. The physical mechanism of the mixing (often called "cool bottom processing" or CBP, [29]) is unknown, but it is likely related to rotation. Again, the high-precision grain data can help constrain parameters of mixing models, for example the mixing rate and temperature reached by circulating material [27]. Interstingly, 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.

There is less compelling evidence for grains from intermediate-mass (IM) stars (2–8 $M_\odot$). Lugaro et al. [30] argued for an IM-AGB origin for an unusual presolar $MgAl_2O_4$ grain, on the basis of O and Mg isotopes. However, this appears to be inconsistent with more recent determinations of key nuclear reaction rates (M. Lugaro, pers. comm.) and the origin of this grain is currently ambiguous.

Supernovae and Novae

A small fraction of presolar SiC ("X grains"), the very rare Si_3N_4 grains and a larger fraction of presolar graphite grains are believed to originate in the cooling ejecta of Type II supernovae (SNe). The most compelling evidence for this origin is the observation of large ^{44}Ca excesses, unaccompanied by anomalies in other stable Ca isotopes, in many grains [31, 32, 33]. This signature points to *in situ* decay of ^{44}Ti, which has a half-life

of $\approx$60 y and is produced solely in SNe. Moreover, extinct ^{49}V observed in some grains [34] 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 point to a SNe origin as well, and, as for the AGB-derived grains, the data can provide new astrophysical information. 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 [32, 35, 36]. 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.*, [37]).

The SN grains have provided several interesting and important insights into supernova nucleosynthesis. 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 [38]. Moreover, the grains are uniformly more ^{15}N-rich (Fig. 3) than can be explained by the SN mixing models. This result and some astronomical observations [39] indicate that Type II SNe are a major producer of ^{15}N, even though this is not predicted by state-of-the-art calculations (e.g., [40]). As in the case of mixing in low-mass AGB stars (previous section), the solution to this discrepancy between theory and observation may lie in multiple dimensions: models of rotating massive stars appear to produce larger amounts of ^{15}N during core He-burning than 1-d models predict [41], but clearly this problem requires much more attention. Finally, extremely unusual Ca and Ti isotopic compositions were recently reported in presolar SN graphite grains [42]. 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.

In addition to SN C- and N-rich phases, a small fraction of presolar oxide and silicate grains also likely formed in SNe. Interestingly, although the most abundant product of Type II SNe is ^{16}O, only one ^{16}O-rich SN grain has been found [43]. The remainder of O-rich grains believed to have a SN origin are ^{18}O-rich [44, 18], reflecting a contribution from the He-burning zone of the massive star (Fig. 1). That a majority of presolar SN O-rich grains are apparently from outer layers of the parent stars might reflect preferential destruction of dust grains in deeper layers by reverse shocks [45].

Amari et al. [46] proposed a nova origin for a handful of isotopically unusual SiC and graphite grains, based mostly on very low ^{12}C/^{13}C and ^{14}N/^{15}N ratios (Fig. 3), but also on ^{30}Si enrichments. However, a nova origin for these grains is somewhat problematic because huge dilution of the pure nova nucleosynthetic signatures is required to explain the data. Moreover, Nittler and Hoppe [47], reported a SiC grain with very similar C and N isotopes to the putative nova grains, but with Si, Mg, Ca and Ti isotopic ratios strongly indicative of a supernova origin. This result shows that SNe can produce compositions with lower ^{12}C/^{13}C and ^{14}N/^{15}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. 3, [22]) with ^{12}C/^{13}C=1, low ^{14}N/^{15}N and high inferred ^{26}Al/^{27}Al. This grain's composition agrees well with nova models [48], without any dilution and is the strongest candidate found to date for a nova condensate in a meteorite.

Galactic Chemical Evolution

The isotopic composition of a given star (and hence grains that condense from it) depends both on the initial composition with which it was born and any nuclear processing that occurs within during its evolution. The initial compositions are set by Galactic chemical evolution (GCE). Stars born at different times and places have different isotopic compositions due to the different nucleosynthetic origins of different isotopes. This is reflected in the isotopic compositions of some elements in presolar grains and thus the grains can also provide constraints on GCE. For example, most of the Si and Ti isotopic ratios of presolar SiC grains appear to be dominated by GCE effects [49, 26]. Although there are many puzzles, the grain data have been used to argue that the Sun might have an atypical isotopic composition for its age [26, 50], that the interstellar medium is well mixed [51], and that the formation of the presolar grain parent stars might have been triggered by a collision between the Milky Way and a dwarf galaxy [52]. Similarly, GCE clearly played a role in setting the Mg and Ca isotopic compositions measured in presolar oxide grains [53, 18].

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