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What can pre-solar grains tell us about AGB stars?

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Abstract. Small amounts of pre-solar grains have survived in the matrices of primitive meteorites and interplanetary dust particles. Their detailed study in the laboratory with modern analytical tools provides highly accurate and detailed information with regard to stellar nucleosynthesis and evolution, grain formation in stellar atmospheres, and Galactic Chemical Evolution. Their survival puts constraints on conditions they were exposed to in the interstellar medium and in the Early Solar System.

Keywords. Keyword1, keyword2, keyword3, etc.

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1. Introduction

Almost twenty years have passed since, as a result of the search for host phases of isotopically unusual noble gases, the first discovery in 1987 of surviving pre-solar minerals (diamond and silicon carbide) in primitive meteorites. These were followed by others (graphite, refractory oxides, silicon nitride, and finally silicates) in the years since. Pre-solar grains occur in even higher abundance than in meteorites in interplanetary dust particles (IDPs). The result is a kind of 'new astronomy' based on the study of pre-solar condensates with all the methods available in modern analytical laboratories.

In the 'classical' approach, pioneered in the search for the noble gas carriers diamond, SiC and graphite, pre-solar grains are isolated by dissolving most of the meteorites (consisting mostly of silicate minerals) using strong acids, followed by further chemical and physical separation methods. For overviews at the early stage when only these types were known see reviews by Anders & Zinner (1993) and Ott (1993).

More up-to-date reviews (although only barely including the only recently found pre-solar silicates) are by Zinner (1998), Hoppe & Zinner (2000), Nittler (2003), and Zinner (2004). Refractory oxides and silicon nitride were found in conjunction with the noble gas carrying minerals because of their similar chemical inertness which allowed them to survive the extraction procedure of the noble gas carriers. Identification of pre-solar silicates among the sea of 'normal silicates', however, became possible only with the advent of a new generation of analytical instrumentation, the NanoSIMS (e.g., Hoppe et al. 2004) that allowed the imaging search for isotopically anomalous phases in situ, i.e. without the need for chemical / physical extraction.

Central to the identification of pre-solar minerals is the determination of isotopic compositions, which as a rule strongly deviate from the normal (Solar System) composition. Isotopic composition is, as a matter of fact, the main (and only safe) criterion by which they can be identified; hence all our known 'pre-solar grains' are 'circum-stellar condensates' that carry the isotopic signatures of nucleosynthesis processes going on in their parent stars (Fig. 1).

Because pre-solar grains come from different stellar sources, information on individual stars can only be obtained by the study of single grains. This is possible by SIMS (Secondary Ion Mass Spectrometry) for the light to intermediate-mass elements, RIMS (Resonance Ionization Mass Spectrometry) for the heavy elements, and laser heating and gas mass spectrometry for He and Ne.

2. Overview

An overview of the currently known inventory of circumstellar grains in meteorites is presented in Table 1. Abundances of silicates are definitely, those of the other pre-solar grains most likely, higher in IDPs. Some comments follow below, while several specific cases are discussed in detail in other contributions to this volume.

Silicon carbide. All SiC grains in primitive meteorites are of pre-solar origin, and they are the best characterized. This has been helped by their comparably high contents of minor and trace elements. Characteristic for most grains are enhanced ^{13}C, ^{14}N, former presence of ^{26}Al as indicated by overabundances of its daughter ^{26}Mg, neon that is almost pure ^{22}Ne [Ne-E(H)] and heavy elements showing the characteristic isotopic signatures of the s-process. These 'mainstream grains' quite obviously are condensates out of the winds of AGB stars (see contribution by Lugaro & Höfner, this volume). Only a percent or so have a clearly different origin tied to supernovae (the 'X-grains'). They are characterized by high ^{12}C, ^{28}Si, very high former abundances of ^{26}Al as well as ^{44}Ti and not fully understood signature in the heavy trace elements (see contribution by Amari & Lodders, this volume).

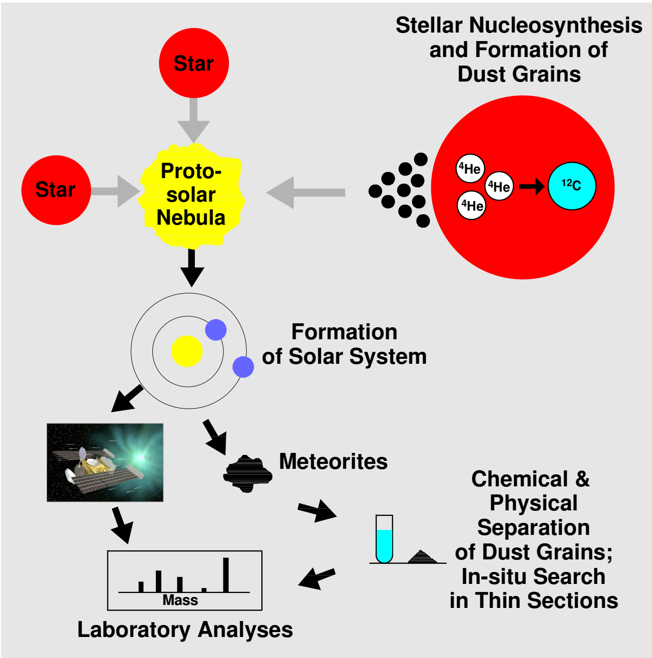

Figure 1. Path of pre-solar grains from their stellar sources to the laboratory.

Table 1. Overview of current knowledge on circum-stellar condensate grains in meteorites.

Mineral	**Size** [μm] **abund.** [ppm][1]	**Isotopic Signatures**	**Stellar Sources**	**Contri-bution**[2]
diamond	0.0026 1500	Kr-H, Xe-HL, Te-H	supernovae	?
silicon carbide	0.1 – 10 30	enhanced ^{13}C, ^{14}N, ^{22}Ne, s-process elem. low ^{12}C/^{13}C, often enh. ^{15}N enhanced ^{12}C, ^{15}N, ^{28}Si; extinct ^{26}Al, ^{44}Ti low ^{12}C/^{13}C, low ^{14}N/^{15}N	AGB stars J-type C-stars (?) Supernovae novae	> 90 % < 5 % 1 % 0.1 %
graphite	0.1 – 10 10	enh. ^{12}C, ^{15}N, ^{28}Si; extinct ^{26}Al, ^{41}Ca, ^{44}Ti s-process elements low ^{12}C/^{13}C low ^{12}C/^{13}C; Ne-E(L)	SN (WR?) AGB stars J-type C-stars (?) novae	< 80 % > 10 % < 10 % 2 %
corundum/ spinel/ hibonite	0.1 – 5 50	enhanced ^{17}O, moderately depl. ^{18}O enhanced ^{17}O, strongly depl. ^{18}O enhanced ^{16}O	RGB / AGB AGB stars supernovae	> 70 % 20 % 1 %
silicates	0.1 – 1 140	similar to oxides above		
silicon nitride	1 0.002	enhanced ^{12}C, ^{15}N, ^{28}Si; extinct ^{26}Al	supernovae	100 %

Notes:
[1]For the abund. (in wt. ppm) the reported maximum values from different meteorites are given.
[2]Note uncertainty about actual fraction of diamonds that are pre-solar and for fraction of graphite attributed to SN and AGB stars (see discussion in text).

Oxides and silicates. Besides diamonds (see below) silicates - not unexpectedly - are the most abundant of the pre-solar grains that have been found. The most characteristic features of oxides and silicates are contained in the oxygen isotopic composition that can be used for assigning each grain to one of four groups (Nittler et al. 1997). Grains without evidence for the former presence of ^{26}Al are assumed to originate from RGB stars, those with ^{26}Al from AGB stars.

Graphite and silicon nitride. The characteristics of most grains (see Tab. 1) have traditionally led to assume a SN origin (e.g., Zinner 1998; Hoppe & Zinner 2000). However, this percentage may have been overestimated as most high-density graphite grains, although showing enhanced ^{12}C abundances, contain s-process signatures and so are more likely to originate from AGB stars (Croat et al. 2005). The rare Si_3N_4 grains show isotopic signatures similar to SiC-X and SN graphite grains and derive probably from supernovae as well.

Nanodiamonds. In several ways these are the most enigmatic. Although discovered first, their pre-solar credentials are based solely on trace elements Te and noble gases that they carry. They are too small for individual analysis each consisting of some 1000 carbon atoms only on average and the carbon isotopic composition of 'bulk samples' (i.e., many diamond grains) is within the range of Solar System materials. What fraction of the diamonds is truly pre-solar is an as yet open question.

3. Implications

Isotopic structures and nucleosynthesis. As isotopic structures are the key for establishing the grains as pre-solar, isotope studies are at the core of investigations that have been performed. Results from isotopic studies in turn are also those that bear strongest on astrophysics. For one, they allow us to pinpoint the grains' stellar sources. In addition, given the precision of the laboratory isotopic analyses, which far exceed whatever can be hoped for in remote analyses, they allow conclusions with regard to details of nucleosynthesis and mixing in the parent stars as well as Galactic Chemical Evolution. They have borne strong on, e.g. the need for an extra mixing process (cool bottom processing) in Red Giants and provide detailed constraints on the operation of the s-process in AGB stars (e.g., Busso et al. 1999). A non-standard neutron capture process ('neutron burst') may be implied by the SiC-X grains from supernovae (Meyer et al. 2000) and possibly the trace Xe in the diamonds (e.g., Ott 2002). The progress in analytical techniques promises more important results in the near future.

Grain formation. Chemical composition, sizes, and microstructures of grains constrain conditions during condensation in stellar winds and supernova ejecta. Condensation of SiC apparently occurred under close to the equilibrium conditions (e.g., Lodders & Fegley 1998). Additional constraints are imposed by trace element contents both on average (Yin et al. 2006) as well as in individual grains (Amari et al. 1995). An important relevant observation is the occurrence of subgrains of primarily TiC within graphite (Croat et al. 2005).

The lifecycle of pre-solar grains (and maybe interstellar grains in general). Interstellar grains are expected to be processed and eventually destroyed by sputtering or astration (e.g., Draine 2003), with an as yet unidentified process needed to account for the balance between formation and destruction. Pre-solar grains preserved in meteorites carry, in principle, a record of conditions they have been exposed to, which, however, is difficult to read. Determining an absolute age using long-lived radioisotopes is virtually ruled out by the fact that these systems use decay of rare constituents (e.g., K, Sr, Re, U) decaying into other rare elements with uncertain non-radiogenic composition. However, appearance and microstructures of pristine (i.e. not chemically processed) SiC show little evidence for being processed, indicating either that they were surprisingly young when entering the forming Solar System or that they were protected (Bernatowicz et al. 2003); a similar situation is indicated by the lack of detectable spallation Xe produced by exposure to cosmic rays during residence in the ISM (Ott et al. 2005). The distribution, finally, among various types of meteorites, provides a measure of processing in the early Solar System.

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Discussion

MASSEY: Im wondering if you have considered the expected intrinsic dispersion in absolute magnitude of WRs – if you consider the (large) mass range that becomes an early WN or late WC according to the evolutionary models, wouldnt you expect a large dispersion in M_v?

VAN DER HUCHT: Indeed, we will be always left with some intrinsic scatter in M_v due to mass differences within the same spectral subtype. But in my opinion, the current large dispersion is for a large fraction due to incertainties of the adopted distances of open clusters and OB associations.

WALBORN: I think that the scatter in WNL absolute magnitudes is dominated by intrinsic spread rather than errors. In the LMC, one finds a range of 5 to nearly 8. This in turn likely reflects different formation channels: mass-transfer binaries, post-RSG, and extremely massive stars in giant H II regions.

VAN DER HUCHT: As said above, there is likely to be intrinsic scatter. But, I wonder whether a scatter of 3 magnitudes perhaps reflects undetected multiplicity.

MAÍZ-APELLÁNIZ: I could not agree more with your comment on the need for an updated catalogue of O-type stars (as a follow up of that of Garmany *et al.* 1982). We are currently working on precisely that (see our poster, these Proceedings) and we will soon make it available.

VAN DER HUCHT: Wonderful.

KOENIGSBERGER: Is the ratio WR/O-stars in clusters similar or different from this ratio for the field stars?

VAN DER HUCHT: I think it is different because incompleteness among field stars is even larger than that among cluster stars. But perhaps it should also be different because WR stars are older and could have drifted away from clusters, more than O-type stars.

GIES: How many of the WR stars in your catalogue might be low mass objects?

WALBORN: Comment: PN central stars in the WR sample would be only [WC].

VAN DER HUCHT: Among the WR stars in our VIIth Catalogue we doubt only one: WR109 (V617 Sgr), which is a peculiar object (not even a [WR] central star of a PN). All other stars in our cataloge are true massive Population I WR stars, and properly classified as such. We have not listed known Population II [WC] objects, as we did separately in our VIth Catalogue (van der Hucht *et al.* 1981). [WN] objects are not known to exist, see the comment by Nolan.

ZINNECKER: Are all Galactic WR stars in open clusters and OB association or are there many WR stars in the field?

van der Hucht: See the VIIth WR catalogue (van der Hucht 2001): of the listed 227 Galactic WR stars, only 53 are in open culsters and OB associations, or believed to be. The other 184 are supposedly field stars.