REVIEW

Recent Studies of Presolar Grains

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Presolar grains are defined as grains which had formed in the circumstellar envelope or supernova ejecta and remain intact during the formation of the solar system. They have been extensively studied during the last 10 years. They exhibit huge isotopic anomalies, confirming their stellar origin. SIMS (Secondary Ion Mass Spectrometry) has proved itself to be a very powerful tool to study presolar grains. Isotopic ratios of more than one elements can be measured if grains are 1 μm or larger in size. Several kinds of stars have been identified as stellar sources of presolar grains. One type is AGB (Asymptotic Giant Branch) stars and another type is supernovae (SNe). Most presolar SiC grains (about 93%) exhibit $^{12}\text{C}/^{13}\text{C}$ ratios ranging from 30 to 100 and are called mainstream SiC grains. Their C and N isotopic ratios generally agree with what is expected from the evolution of AGB stars. Silicon isotopic ratios of the grains show excesses in ^{29}Si and ^{30}Si . To explain the Si-isotopic ratios, Galactic chemical evolution or inhomogeneity of the ISM (Interstellar Medium) has to be invoked. Silicon carbide of type X (about 1% of total SiC), low-density graphite, and silicon nitride are most likely to have formed in supernova ejecta. Many grains have ^{28}Si excesses and a few grains show the presence of ^{44}Ti . These features are considered to be a proof of their supernova origin. The comparison with theoretical calculations of nucleosynthesis in supernova suggests that extensive and heterogeneous mixing occurs when supernovae explode.

1. Introduction

Since the discovery of presolar diamond in the Allende meteorite in 1987,¹⁾ presolar grains have been extensively studied and a respectable amount of information has been obtained. Overall aspects of the field are covered by several reviews.²⁾⁻⁴⁾

Presolar grains are defined as grains which had formed in the circumstellar envelope or in supernova which survived subsequent events in the solar system, thus preserving information of their parent stars. They usually exhibit huge isotopic anomalies.

Up to date, only chemically-resistant presolar grains are extracted from meteorites. Figure 1 shows their abundances, sizes and their proposed stellar sources. Even most abundant type of presolar grains, diamond, comprises only 500 ppm of bulk meteorites. Thus they are extremely rare in meteorites.

Although a new type of instrument, RIMS (resonance ionization mass spectrometry), has been successfully applied for isotopic analyses of heavy trace elements,^{5), 6)} most isotopic data on individual grains have been obtained by SIMS. However, with the present technology, grains have to be relatively large ($>1 \mu\text{m}$) in order to obtain isotopic ratios of several elements with reasonable errors. Isotopic analyses revealed a large diversity among individual grains.

Studies of presolar grains have provided invaluable astronomical information on nucleosynthesis in stars and the mixing of supernova ejecta. Two examples are shown in the following sections.

2. Mainstream SiC Grains

The "mainstream" component, which accounts for 93% of all SiC,^{7), 8)} are believed to come from thermally-pulsing (TP) AGB stars. The best evidence for such an origin is the s-process (slow neutron capture process) isotopic patterns displayed by the heavy elements Kr, Sr, Zr, Mo, Xe, Ba, Nd, and Sm.^{5), 6), 8)-12)} Gallino *et al.*¹²⁾ successfully reproduced the measured s-process compositions of the heavy elements in mainstream SiC grains with models of low-mass AGB stars of close-to-solar metallicity.

The C and N isotopic compositions as well as $^{26}\text{Al}/^{27}\text{Al}$ ratios of individual mainstream SiC grains are by and large consistent with a carbon star origin.^{8), 13)} In contrast to C, N, Al, and the heavy elements, the variations in the Si isotopic ratios measured in single mainstream grains (see the grain data in Fig. 2) cannot be explained in terms of nucleosynthesis in AGB stars.

Fig. 1. Abundances and grain sizes of presolar grains extracted from meteorites. Proposed stellar sources and names of the anomalous noble gases which are carried by them are indicated.

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Fig. 2. Silicon isotopic ratios measured in mainstream SiC grains plotted as σ -values (open squares) are compared with the results of Monte Carlo calculations (filled circles) in which contributions from different SN sources are added to a starting isotopic composition in a random way (from paper by Lugaro *et al.*²¹⁾). In each case 200 compositions are plotted. Starting composition: $\sigma^{29}\text{Si}/^{28}\text{Si} = \sigma^{30}\text{Si}/^{28}\text{Si} = -100\%$; N (the number of SN contributed to the ISM) = 420; a (the fraction taken from each SN source) = 1.1×10^{-5} . $\delta^i\text{Si}/^{28}\text{Si} (\%) \equiv [(^i\text{Si}/^{28}\text{Si})_{\text{Measured}} / (^i\text{Si}/^{28}\text{Si})_{\text{Solar}} - 1] \times 1,000$.

They have been interpreted as variations in the initial Si isotopic compositions of the AGB stars that contributed SiC grains to the solar system. Variations of the initial Si compositions are expected as the result of GCE (Galactic Chemical Evolution).

Timmes and Clayton¹⁴⁾ and Clayton and Timmes^{15), 16)} constructed a detailed model of the Galactic history of the Si isotopes which is based on the GCE model of Timmes, Woosley and Weaver.¹⁷⁾ The SN production yields were obtained from the Type II SN models of Woosley and Weaver¹⁸⁾ and from the popular W7 Type Ia SN model by Thielemann, Nomoto, and Yokoi.¹⁹⁾ Their result shows that a continuous increase of the $^{29}\text{Si}/^{28}\text{Si}$ and $^{30}\text{Si}/^{28}\text{Si}$ ratios is expected throughout Galactic history.

According to the Timmes and Clayton model,¹⁴⁾ the spread in the isotopic compositions of the mainstream grains corresponds to variations in the birth dates of their parent stars. The birth dates of the parent stars range over ~ 5 Gyr. However, a fundamental problem of this model is that mainstream grains are inferred to be younger than the sun, since most of them have $^{29}\text{Si}/^{28}\text{Si}$ and $^{30}\text{Si}/^{28}\text{Si}$ ratios that are larger than those of the solar system. This absurd corollary of the model led Clayton²⁰⁾ to consider the possibility that the mainstream grains originated from stars that were born at different Galactic radii than the sun.

Lugaro *et al.*¹⁾ have taken a different approach to explain the Si-isotopic variation of SiC grains. In the Galaxy as a whole, ^{29}Si and ^{30}Si will monotonically increase with time. However, due to the stochastic nature of SN contributions to a given region and the

large range in Si isotopic ratios of different SN sources, fluctuations of the Si ratios of different regions are expected, even for a given time and galactic radius. It is unlikely that these discrete contributions are instantly mixed with preexisting material so that the isotopic compositions of large Galactic regions are completely homogenized.

They have performed a Monte Carlo calculation in which contributions from discrete SN sources were added in a statistical way to material with an arbitrary (but reasonable) Si isotopic composition. As SN sources they considered SNIIe of solar metallicity from the Woosley & Weaver model¹⁸⁾ (80%), Type Ia SNe of the W7 model²²⁾ (12%), and sub-Chandrasekhar SNe of Type I²³⁾ (8%). They also assigned weights according to $M^{-1.35}$ to SNIIe of different masses. They found that for a wide range of starting compositions the Si isotopic compositions of the mainstream grains can be reproduced surprisingly well if they adjusted the total number of SNe from which contributions were randomly selected and the fraction contributed by each SN.

3. Supernova Grains

Of supernova grains, SiC X grains^{24), 25)} comprise about 1% of total presolar SiC grains and show a distinct isotopic feature which is different from those of other types of SiC grains. Low-density graphite grains^{26, 27)} are in the density range of 1.72–2.10 g/cm³. Silicon nitride (Si_3N_4)²⁵⁾ is the least abundant type of grains among the three kinds of SN grains.

The strongest evidence of their supernova origin is the presence of ^{44}Ti ($T_{1/2}=60\text{a}$) inferred from excesses of ^{44}Ca observed in a few grains. One graphite grain shows the ^{44}Ca excess $137\times$ solar, while other Ca-isotopic ratios are normal within huge 2σ errors.²⁸⁾ This leaves little doubt that the excess is due to the decay of ^{44}Ti , not from other nuclear reactions such as n -capture. ^{44}Ti is produced only in supernovae. Inferred $^{44}\text{Ti}/^{48}\text{Ti}$ ratios of the grains range from 1×10^{-3} up to 0.37 ^{28), 29)} (Fig. 3f).

Another evidence of their supernova origin is that all the X grains, Si_3N_4 and many low-density graphite grains show ^{28}Si excesses up to $5\times$ solar (Fig. 3e). ^{28}Si is produced by O-burning in Type II supernovae. Interestingly, in Type II supernovae, both ^{28}Si and ^{44}Ti are produced in the O-rich zones. Grains with ^{44}Ti and ^{28}Si excesses most likely have condensed in supernova ejecta. Unfortunately, it is not feasible to measure Si- and Ca-Ti-isotopic ratios for all the grains, thus we can infer their origin only from isotopic ratios of other elements such as C, N, and $^{26}\text{Al}/^{27}\text{Al}$ ratios. Grains with ^{44}Ti and ^{28}Si excesses have distinct isotopic features for other elements. If grains show the same isotopic features as those that are of a supernova origin, they also formed in the same type of stars—supernovae.

A Type II supernova consists of layers where different nucleosynthetic reactions take place. Of them the He/N, He/C, and C/O zones are the places where C/O ratios >1 (Names of zones are coined according to Meyer *et al.*,³⁰⁾ indicating the most abundant elements in the zones). This condition is necessary to form carbonaceous grains. In the He/N zone, ^{13}C and ^{14}N

Fig. 3. Isotopic ratios of SN grains and the mixing calculated by Travaglio *et al.*³⁰ using a $15 M_{\odot}$ model by Woosley and Weaver.¹⁸ Solid circles indicate low-density graphite, open squares indicate SiC type X, and solid triangles indicate SiC type B. Various lines represent different ratios of M5/M2 and M6/M2 to the resulting mix. Ranges which satisfy condition of $C/O > 1$ and $^{12}C/^{13}C$ ratios between 5 and 10^4 are shown. a) ^{14}N in the M1 zone is reduced by a factor of 20. Still the mix falls short of ^{15}N , grains with low $^{14}N/^{15}N$ ratios not being explained. b) In addition to reducing ^{14}N in the M1 zone, ^{15}N in the M2 zone is increased by a factor of 5. c) To reproduce the range of ^{18}O excesses in low-density graphite grains, various amount of contribution from O-rich M5 zone is required. d) The ratios of the mix are in a narrow bands and quite a few grains are outside of the range. e) To reproduce the ^{28}Si excesses, contribution from the M6 zone is necessary. However, many grains lie above the mixing lines, indicating ^{29}Si is deficient in the model. See the text. $\delta^{30}Si/^{28}Si$ ratios of the grains range from 1×10^{-3} up to 0.37.

become highly enriched through CNO cycle and ^{26}Al by $^{25}Mg(p, \gamma) ^{26}Al$. In the He/C zone, ^{12}C is produced by He-burning and ^{14}N is rapidly destroyed and converted into ^{18}O . ^{15}N becomes also depleted in this zone during hydrostatic burning, while produced at the bottom of the zone by explosive nucleosynthesis. Woosley and Weaver¹⁸ predicted $^{26}Al/^{27}Al$ ratio to be 0.24 in the He/N zone and $^{16}O/^{18}O$ ratio in the He/C zone to be 0.37 in a $15 M_{\odot}$ model with solar metallicity.

We note that supernova grains show features of both zones, high $^{26}Al/^{27}Al$ ratios (Fig. 3d) reflecting contribution from the He/N zone, low $^{16}O/^{18}O$ ratios in graphite grains (Fig. 3c) and high $^{12}C/^{13}C$ ratios (Fig. 3a) from the He/C zone. However, some of the ratios in the zones are far too anomalous than what are observed in the grains, requiring mixing between the zones. For example, C in the He/C zone is essentially ^{12}C and the mixing with C in the He/N zone would be required to

reproduce the observed range.

It is also required to have material from the innermost O-burning zones mixed into those of the C-rich zones to explain ^{28}Si excesses and the presence of ^{44}Ti of the grains, since ^{28}Si is produced by hydrostatic and explosive nucleosynthesis and ^{44}Ti by explosive nucleosynthesis in the O-burning zones. Between these zones are the huge O-rich zones. To have the isotopic characteristics of the grains, mixing during the explosion should be very extensive so that the outer He-rich zones and the innermost O-rich zones are involved. At the same time, it should be heterogeneous to avoid to incorporate the huge O-rich zones in-between to fulfill a condition of C/O ratio > 1 for the mix to form carbonaceous grains.

Travaglio *et al.*³⁰ and Zinner *et al.*²⁹ have performed mixing calculations in order to quantitatively examine the mixing and to reproduce isotopic data of low-

Fig. 4. Travaglio *et al.*³¹⁾ divided a 15 $M_{\odot}$ supernova by Woosley and Weaver¹⁸⁾ into seven different zones. The zones M1, M2, and M3 have $C>O$, zones M4 and M5 are dominated by ^{16}O and zone M6 is dominated by ^{28}Si , and zone M7 is dominated by ^{56}Ni .

density graphite grains and other SN grains by using Type II supernova models by Woosley and Weaver.¹⁸⁾ We will briefly summarize their results and discussions^{31), 32)} here.

They divided zones of a supernova into 7 zones, M1, M2, M3 being He-rich, M4 and M5 being O-rich, M5 and M6 being Si-rich, and M7 being Ni-rich (Fig. 4). They mixed those zones so that the resulting mix should have a condition of $C/O>1$ and $^{12}C/^{13}C$ ratios would be in the range of 5 to 10^4 . The contribution from zone M4 is fixed and that of M5 and M6 are changed. Overall trend and the ranges of the isotopic data can be reproduced by the mixing (see Fig. 3). However, several isotopic features which cannot be explained by the model and the major problems are summarized below.

3.1 ^{15}N deficiency

They found that if all the ^{14}N in M1 (He/N) zone is incorporated in the mix, the N-isotopic ratios become much higher than those observed in the grains. Thus they arbitrarily reduced the amount of ^{14}N in the M1 zone by a factor of 20 (Fig. 3a) and increased ^{15}N in the M2 (He/C) by a factor of 5 (Fig. 3b). Their result strongly suggests that either ^{15}N in the He/C zone is deficient in the model or most ^{14}N in the He/N zone does not go into the grains. The former is quite possible. Langer³³⁾ examined rotational mixing in massive stars and found that by mixing proton into He-rich region, ^{15}N production can be substantially higher than previously predicted. In addition, ^{15}N production during explosive nucleosynthesis strongly depends on the strength of the shock. Thus, the ^{15}N deficiency may well be solved once those terms are taken into account.

3.2 ^{29}Si deficiency

As shown in Fig. 3e, the mix is short of ^{29}Si to reproduce the grain data, most grains being plotted above the lines. It suggests that ^{29}Si is underproduced in the model of Type II. This is strengthened by the fact that Timmes and Clayton¹⁴⁾ failed to explain the cosmic ratio of $^{29}Si/^{30}Si$ (1.7) by using productions of different stellar sources including Type II supernovae.

The deficiency of ^{29}Si relative to ^{30}Si is also observed in another model by Thielemann *et al.*³⁴⁾ and it may be a problem of fundamental parameters in the models.

Travaglio *et al.*³⁵⁾ pointed out that $^{26}Mg(\alpha, n)^{29}Si$ reaction rate can be higher by a factor of 2. It remains to be seen whether this assumption can be justified.

4. Conclusion

As shown in the two examples, isotopic studies of presolar grains can provide detailed and specific information about nucleosynthesis inside the stars and mixing of supernova ejecta, with precisions which cannot be obtained otherwise.

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References

- 1) R. S. Lewis, M. Tang, J. F. Wacker, E. Anders, and E. Steel, *Nature*, **326**, 160 (1987).
- 2) U. Ott, *Nature*, **364**, 25 (1993).
- 3) E. Zinner, "Astrophysical Implications of the Laboratory Study of Presolar Materials," ed. by T. J. Bernatowicz and E. Zinner, AIP, New York (1997), p. 3.
- 4) E. Zinner, *Ann. Rev. Earth and Planet. Sci.*, **26**, 147 (1998).
- 5) G. K. Nicolussi, A. M. Davis, M. J. Pellin, R. S. Lewis, R. N. Clayton, and S. Amari, *Science*, **277**, 1281 (1997).
- 6) G. K. Nicolussi, M. J. Pellin, R. S. Lewis, A. M. Davis, R. N. Clayton, and S. Amari, *Astrophys. J.*, **504**, 492 (1998).
- 7) P. Hoppe, S. Amari, E. Zinner, T. Ireland, and R. S. Lewis, *Astrophys. J.*, **430**, 870 (1994).
- 8) P. Hoppe and U. Ott, "Astrophysical Implications of the Laboratory Study of Presolar Materials," ed. by T. J. Bernatowicz and E. Zinner, AIP, New York (1997), p. 27.
- 9) R. S. Lewis, S. Amari, and E. Anders, *Nature*, **348**, 293 (1990).
- 10) R. S. Lewis, S. Amari, and E. Anders, *Geochim. Cosmochim. Acta*, **58**, 471 (1994).
- 11) R. Gallino, C. M. Raiteri, and M. Busso, *Astrophys. J.*, **410**, 400 (1993).
- 12) R. Gallino, M. Busso, and M. Lugaro, "Astrophysical Implications of the Laboratory Study of Presolar Materials," ed. by T. J. Bernatowicz and E. Zinner, AIP, New York (1997), p. 115.
- 13) G. R. Huss, I. D. Hutcheon, and G. J. Wasserburg, *Geochim. Cosmochim. Acta*, **61**, 5117 (1997).
- 14) F. X. Timmes and D. D. Clayton, *Astrophys. J.*, **472**, 723 (1996).
- 15) D. D. Clayton and F. X. Timmes, "Astrophysical Implications of the Laboratory Study of Presolar Materials," ed. by T. J. Bernatowicz and E. Zinner, AIP, New York (1997), p. 237.
- 16) D. D. Clayton and F. X. Timmes, *Astrophys. J.*, **483**, 220 (1997).
- 17) F. X. Timmes, S. E. Woosley, and T. A. Weaver, *Astrophys. J. Suppl.*, **98**, 617 (1995).
- 18) S. E. Woosley and T. A. Weaver, *Astrophys. J. Suppl.*, **101**, 181 (1995).
- 19) F.-K. Thielemann, K. Nomoto, and K. Yokoi, *Astron. Astrophys.*, **158**, 17 (1986).
- 20) D. D. Clayton, *Astrophys. J.*, **484**, L67 (1997).
- 21) M. Lugaro, E. Zinner, R. Gallino, and S. Amari, *Astrophys. J.*, **527**, 369 (1999).

- 22) K. Nomoto, K. Iwamoto, N. Nakasato, F.-K. Thielemann, F. Brachwitz, T. Tsujimoto, Y. Kubo, and N. Kishimoto, *Nuclear Phys. A*, **A621**, 467c (1997).
- 23) S. E. Woosley and T. A. Weaver, *Astrophys. J.*, **423**, 371 (1994).
- 24) S. Amari, P. Hoppe, E. Zinner, and R. S. Lewis, *Astrophys. J.*, **394**, L43 (1992).
- 25) L. R. Nittler, P. Hoppe, C. M. O. D. Alexander, S. Amari, P. Eberhardt, X. Gao, R. S. Lewis, R. Strebel, R. M. Walker, and E. Zinner, *Astrophys. J.*, **453**, L25 (1995).
- 26) S. Amari, E. Zinner, and R. S. Lewis, *Astrophys. J.*, **447**, L147 (1995).
- 27) S. Amari, E. Zinner, and R. S. Lewis, *Astrophys. J.*, **470**, L101 (1996).
- 28) L. R. Nittler, S. Amari, E. Zinner, S. E. Woosley, and R. S. Lewis, *Astrophys. J.*, **462**, L31 (1996).
- 29) P. Hoppe, R. Strebel, P. Eberhardt, S. Amari, and R. S. Lewis, *Science*, **272**, 1314 (1996).
- 30) B. S. Meyer, T. A. Weaver and S. E. Woosley, *Meteoritics*, **30**, 325 (1995).
- 31) C. Travaglio, R. Gallino, S. Amari, E. Zinner, S. Woosley, and R. S. Lewis, *Astrophys. J.*, **510**, 325 (1999).
- 32) E. Zinner, S. Amari, L. R. Nittler, C. Travaglio, R. Gallino, S. Woosley, and R. S. Lewis, *Lunar Planet. Sci.*, **XXIX**, Abstract #1763 (1998).
- 33) N. Langer, A. Heger, S. E. Woosley, and F. Herwig, "Nuclei in the Cosmos V," ed. by N. Prantzos, Editions Frontières, Paris (1998), p. 129.
- 34) F.-K. Thielemann, K. Nomoto, and M.-A. Hashimoto, *Astrophys. J.*, **460**, 408 (1996).
- 35) C. Travaglio, R. Gallino, E. Zinner, S. Amari, and S. Woosley, "Nuclei in the Cosmos V," ed. by N. Prantzos (1998), p. 567.

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