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New Astronomy Reviews 50 (2006) 574–577

New Astronomy Reviews

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The study of radioisotopes in presolar dust grains

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Available online 2 August 2006

Abstract

Presolar grains in primitive meteorites are characterized by large isotopic anomalies in essentially all the analyzed elements. Among these anomalies are excesses in the daughter isotopes of short-lived radioisotopes. These excesses indicate the incorporation of short-lived now extinct isotopes into the grains at the time of their formation. So far laboratory studies of presolar grains have established evidence for the initial presence of the isotopes ^{49}V, ^{22}Na, ^{44}Ti, ^{41}Ca, ^{99}Tc, and ^{26}Al. Evidence for these isotopes have been found in presolar silicon carbide, graphite, and oxide grains from supernovae (^{49}V, ^{22}Na, ^{44}Ti, ^{41}Ca, and ^{26}Al) and AGB stars (^{41}Ca, ^{99}Tc, and ^{26}Al). We analyzed presolar hibonite ($CaAl_{12}O_{19}$) grains, whose oxygen isotopic ratios indicate an origin in AGB stars, for their Al–Mg and Ca–K isotopic systems, determined the initial $^{26}Al/^{27}Al$ and $^{41}Ca/^{40}Ca$ ratios, and compared them with theoretical models of the production of these isotopes in AGB stars. Whereas the abundance of ^{41}Ca, which is produced by neutron capture, agrees with the models, the abundance of ^{26}Al, which is produced by proton capture, greatly exceeds theoretical predictions. The production of this radioisotope requires a process in addition to H shell burning, cool bottom processing.

Keywords: Radioisotopes; Interstellar dust; Supernovae; AGB stars; Nucleosynthesis

Contents

1. Introduction

Primitive meteorites contain tiny mineral grains that have an origin in outflows from evolved stars and in supernova ejecta. These grains survived interstellar travel and the formation of the solar system and are preserved in certain meteorites from which they can be extracted and studied in detail in the laboratory (Nittler, 2003; Zinner, 2004). Their stellar, extra-solar origin is indicated by their isotopic compositions, which are completely different from that of the Solar System. Whereas the latter is a mixture of many stellar sources, any particular presolar grain preserves a record of the isotopic composition of its parent star. Analyses of the isotopic ratios of the grains' elements provide

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1387-6473/$ - see front matter
doi:10.1016/j.newar.2006.06.045

important information about stellar evolution and nucleosynthesis as well as galactic chemical evolution of the isotopes. Secondary ion mass spectrometry (SIMS) with the ion microprobe and resonance ionization mass spectrometry (RIMS) make the isotopic analysis of individual grains possible.

2. Radioisotopes in presolar dust grains

Among the isotopic anomalies found in presolar dust grains are large excesses in certain isotopes that are the daughter isotopes of short-lived radionuclides. These excesses are evidence for the initial presence of the radioisotopes at the time the grains condensed. Table 1 gives a list of radioisotopes, ordered by half life, for which evidence has been found in presolar grains. In addition to the half life and the daughter isotope of each radionuclide, the table also lists the types of presolar grains containing the nuclide and their stellar sources.

Vanadium-49. The typical abundance pattern of the Ti isotopes indicative of the initial presence of ^{49}V is one with a large ^{49}Ti excess (relative to the solar ^{49}Ti/^{48}Ti ratio) and smaller or no excesses for the other Ti isotopes. Such patterns have been measured in SiC grains of type X (Amari et al., 1992; Nittler et al., 1996; Hoppe and Besmehn, 2002) and in graphite grains (Nittler et al., 1996; Travaglio et al., 1999; Stadermann et al., 2005) whose isotopic ratios of other elements indicate a supernova origin. However, large ^{49}Ti excesses by themselves cannot be taken as evidence for ^{49}V because neutron capture in the He/C zone can also produce this isotopic pattern (Woosley and Weaver, 1995; Amari et al., 1996). Hoppe and Besmehn (2002) found a correlation of the ^{49}Ti excesses with the V/Ti ratio in SiC X grains and concluded that they were caused by ^{49}V decay. Travaglio et al. (1999), on the other hand, found that the ^{49}Ti excesses in low-density graphite grains with ^{12}C/^{13}C < 100 can only be explained by mixing of different SN layers if ^{49}V decay is considered. In Type II supernovae ^{49}V is produced by α-rich freezeout in the Si/S and Ni zones via the precursor ^{49}Cr ($T_{1/2} = 42$ min). Si in the Si/S zone is almost pure ^{28}Si and SiC X grains are characterized by large ^{28}Si excesses. Because of its short half life, presolar grains carrying ^{49}V must have condensed within a few months after the explosion.

Sodium-22. The component Ne-E(L), almost pure ^{22}Ne, has led to the identification of presolar graphite (Amari et al., 1990, 1995). In contrast to SiC, where the ^{22}Ne in Ne-E(H) originates from the He-burning shell of AGB stars, most of the ^{22}Ne in presolar graphite grains seems to be of radiogenic origin. Whereas both novae and Type II supernovae are predicted to eject short-lived ^{22}Na, the isotopic ratios of other elements measured in graphite grains indicate a SN origin (Amari, 2006).

Titanium-44. Some SiC grains of type X (Amari et al., 1992; Hoppe et al., 1996, 2000; Nittler et al., 1996; Besmehn and Hoppe, 2003) and graphite grains (Nittler et al., 1996; Travaglio et al., 1999) have ^{44}Ca excesses that are so large (up to more than a factor of 100) that they can only be explained as the result of the decay of ^{44}Ti. A ^{44}Ca excess in an ^{18}O-enriched hibonite grain is also plausibly due to ^{44}Ti (Nittler et al., 2005). Inferred ^{44}Ti/^{48}Ti rations range up to 0.6 and, with the exception of one graphite grain, all grains with evidence for ^{44}Ti have ^{28}Si excesses. Since, as for ^{49}V, ^{44}Ti can only be produced in supernovae (Timmes et al., 1996), its initial presence is evidence for a SN origin of the carrier grains. In Type II supernovae, ^{44}Ti is produced by α-rich freezeout and Si burning in the Si/S and Ni zones, thus its association with ^{28}Si in the grains is no surprise.

Calcium-41. Whereas ^{49}V and ^{44}Ti are made only in supernovae and have therefore been detected only in SN grains, ^{41}Ca is produced by neutron capture on ^{40}Ca in supernovae as well as in AGB stars and has been found in grains from both these stellar sources (Amari et al., 1996; Choi et al., 1999). Another difference is that for ^{49}V and ^{44}Ti the daughter elements are also very refractory. Potassium, on the other hand, is very volatile and is not believed to condense into presolar grains. Thus, whatever K is present is either radiogenic ^{41}K or is contamination (of normal isotopic composition), most likely from the chemical processing of the grains. For ^{41}Ca in AGB grains, see the next section. Evidence for ^{41}Ca was found in SiC X grains (Amari et al., 1997) and low-density grains from supernovae (Amari et al., 1996), with inferred ^{41}Ca/^{40}Ca ratios ranging up to 1.6×10^{-2}. This agrees with theoretical predictions for the He/C, C/O and the O-rich zones of Type II supernovae (Woosley and Weaver, 1995) and is much higher than what is expected for the envelope of AGB stars. Thus, the ratios in these grains provide additional evidence for a SN origin.

Technetium-99. RIMS analysis of the Ru isotopes in individual mainstream SiC grains revealed typical s-process

Table 1
Radioisotopes in presolar grains

Radioisotope	Daughter isotope	Half life	Presolar grain type	Stellar source
^{49}V	^{49}Ti	337 d	SiC, graphite	SNe
^{22}Na	^{22}Ne	2.6 y	graphite	SNe
^{44}Ti	^{44}Ca	60 y	SiC, graphite, hibonite	SNe
^{41}Ca	^{41}K	1.05×10^5 y	SiC, graphite, hibonite	SNe, AGB stars
^{99}Tc	^{99}Ru	2.1×10^5 y	SiC	AGB stars
^{26}Al	^{26}Mg	7.3×10^5 y	SiC, graphite, corundum, spinel, hibonite, silicates	SNe, AGB stars

patterns with variable depletions in all the Ru isotopes relative to the s-process-only ^{100}Ru and terrestrial Ru ratios (Savina et al., 2004). The measured Ru isotopic ratios are in good agreement with theoretical predictions for the s-process in low-mass AGB stars except for relative excesses in ^{99}Ru. These excesses are well explained by the incorporation and decay of ^{99}Tc in the grains. It is fitting that a signature of this element, whose discovery in stars (Merrill, 1952) was the first evidence for stellar nucleosynthesis, is now detected in Stardust studied in the laboratory.

Aluminum-26. This radioisotope is the first for which evidence was found in presolar grains (Zinner et al., 1991) and the one for which exist by far the most data. It has been measured in SiC (for a summary see Zinner, 2004), silicon nitride (Nittler et al., 1995), graphite (Hoppe et al., 1995; Travaglio et al., 1999), corundum (Nittler et al., 1997; Choi et al., 1998), spinel (Zinner et al., 2005), silicate (Nguyen and Zinner, 2004), and hibonite (see the following section). Except for the last two minerals, intrinsic Mg contents are very low so that in many cases Mg in the grains is almost monoisotopic ^{26}Mg of radiogenic origin. The highest inferred ^{26}Al/^{27}Al ratios (up to 0.6) are detected in SiC X and graphite grains from supernovae, where the highest ratios are found in the He/N zone (Woosley and Weaver, 1995). There and in AGB stars ^{26}Al is produced by proton capture on ^{25}Mg. In mainstream SiC grains, ^{26}Al/^{27}Al ratios agree with those predicted for production in the H shell of AGB stars (Forestini et al., 1991; Mowlavi and Meynet, 2000; Karakas and Lattanzio, 2003), but many oxide grains have higher ratios and require an additional process (see Wasserburg et al., in press and next section).

3. Aluminum-26 and ^{41}Ca in presolar hibonite grains

Among presolar grains, hibonite ($CaAl_{12}O_{19}$) is very rare and until recently only a handful of such grains have been known (Choi et al., 1999; Krestina et al., 2002). By automatically measuring the O isotopes of ~7000 grains in an oxide-rich residue from the Krymka (LL3.1) ordinary chondrite with the Carnegie ims 6f ion microprobe we recently identified 21 presolar hibonite grains (Nittler et al., 2005 and unpublished). Their O isotopic ratios are shown in Fig. 1 together with those of other oxide grains. Compared to other oxide phases, hibonite has the advantage that Al and Ca are major elements, allowing Al–Mg and Ca–K analysis to detect fossil ^{26}Al and ^{41}Ca. In addition, Mg and Ti contents are often high enough that the ^{25}Mg/^{24}Mg ratio, and possibly Ti isotopic ratios, can be measured.

With the Washington University NanoSIMS ion probe we analyzed the Al–Mg and Ca–K isotopic systems of the presolar Krymka hibonite grains. Fifteen of them show evidence for extinct ^{26}Al and 10 for ^{41}Ca. The inferred ^{26}Al/^{27}Al and ^{41}Ca/^{40}Ca ratios are plotted in Fig. 2 and compared to theoretical predictions for low-mass AGB stars.

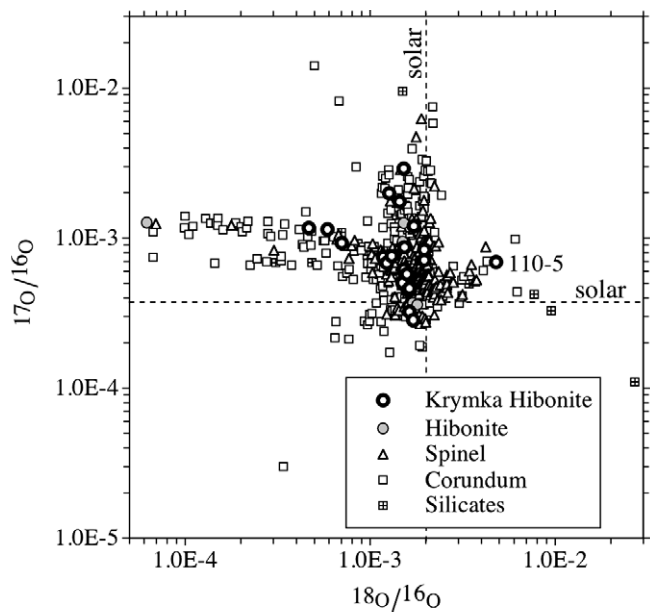

Fig. 1. Oxygen isotopic ratios of Krymka hibonite grains are compared with those of other oxide grains.

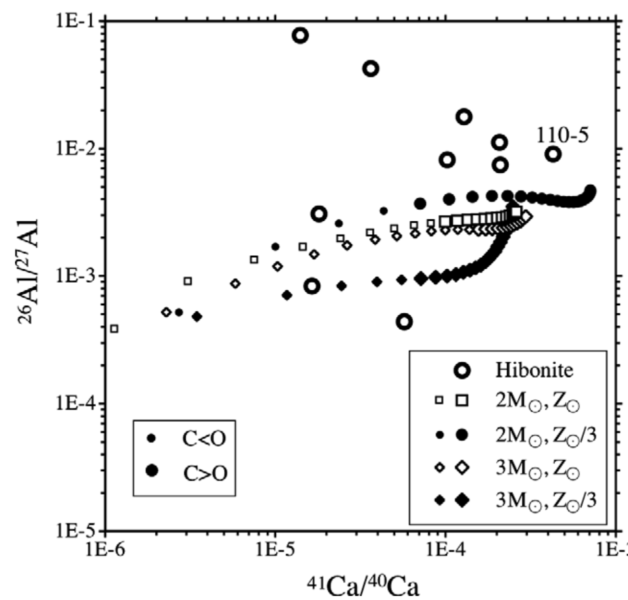

Fig. 2. ^{26}Al/^{27}Al and ^{41}Ca/^{40}Ca ratios of Krymka hibonite grains are plotted together with model predictions for AGB stars of different masses and metallicities.

Whereas the measured ^{41}Ca/^{40}Ca ratios agree with predictions for O-rich AGB stars within a factor of two (the O and other isotopic ratios for grain 110-5 indicate that it has a SN origin), the measured ^{26}Al/^{27}Al ratios are much higher than predicted. The same situation has previously been observed for corundum (Nollett et al., 2003) and spinel (Zinner et al., 2005) grains. Nollett et al. (2003) extended cool bottom processing (CBP), an extra mixing process originally invoked to explain the large ^{18}O depletions found in many presolar oxide grains (Fig. 1) (Wasserburg et al., 1995), to include ^{26}Al production. This mixing

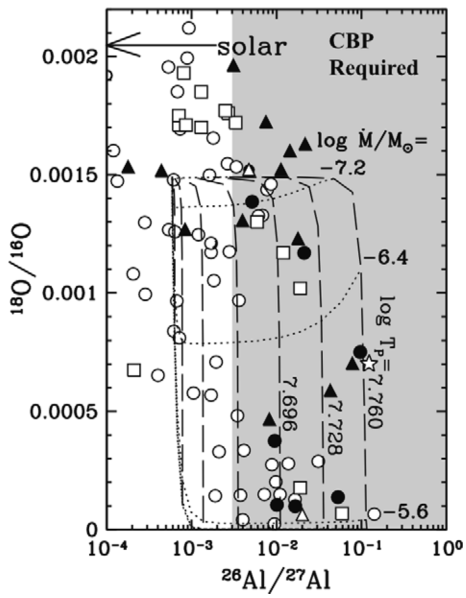

Fig. 3. $^{26}Al/^{27}Al$ and $^{18}O/^{16}O$ ratios of presolar oxide grains (triangles: hibonite, circles: corundum, squares: spinel, star: silicate; filled symbols are recent data from the Krymka meteorite, Nittler et al., 2005) are compared to the CBP model of Nollett et al. (2003). The lines indicate model predictions for constant circulation rate dM/dt (dotted curves) and constant temperature reached (dashed curves). The numbers indicate numerical values for these parameters, solar masses per year for the circulation rate and Kelvin for the temperature. Grains in shaded region have $^{26}Al/^{27}Al$ ratios too high to be explained by shell H burning, but consistent with CBP. Figure adapted from Fig. 6 of Nollett et al. (2003).

process takes material in the star's envelope to hot regions close to the H-burning shell. The parametric model by Nollett et al. (2003) contains two parameters: the circulation rate, which mostly affects the $^{18}O/^{16}O$ ratio, and the temperature reached by the circulated material, which mostly affects the $^{26}Al/^{27}Al$ ratio. In Fig. 3 we superimpose the Al and O ratios in the presolar hibonite grains together with those in presolar spinel (Zinner et al., 2005), in a presolar silicate (Nguyen and Zinner, 2004) and in recently analyzed corundum grains from Krymka (Nittler et al., 2005) onto the original plot (their Fig. 6) by Nollett et al. (2003).

Oxygen-18/oxygen-16 ratios larger than 10^{-3} can be accounted for by the first and second dredge-up (Boothroyd et al., 1994; Boothroyd and Sackmann, 1999) and $^{26}Al/^{27}Al$ ratios smaller than $\sim 3\times10^{-3}$ by shell H burning (Forestini et al., 1991; Mowlavi and Meynet, 2000; Karakas and Lattanzio, 2003). Grains with smaller $^{18}O/^{16}O$ and/or larger $^{26}Al/^{27}Al$ ratios require CBP (Fig. 3). $^{26}Al/^{27}Al$ ratios in hibonite grains reach almost the same values as those in a silicate grain and two corundum grains, corresponding to a temperature of 5.8×10^{7} K according to the Nollett et al., 2003) model. We conclude that presolar hibonite grains provide additional evidence for CBP occurring in O-rich AGB stars.

References

Amari, S., 2006, this volume.
Amari, S., Anders, E., Virag, A., Zinner, E., 1990. Nature 345, 238.
Amari, S., Hoppe, P., Zinner, E., Lewis, R.S., 1992. ApJ 394, L43.
Amari, S., Lewis, R.S., Anders, E., 1995. Geochim. Cosmochim. Acta 59, 1411.
Amari, S., Zinner, E., Lewis, R.S., 1996. ApJ 470, L101.
Amari, S., Nittler, L.R., Zinner, E., Lewis, R.S., 1997. Lunar Planet. Sci. XXVIII, 33.
Besmehn, A., Hoppe, P., 2003. Geochim. Cosmochim. Acta 67, 4693.
Boothroyd, A.I., Sackmann, I.-J., 1999. ApJ 510, 232.
Boothroyd, A.I., Sackmann, I.-J., Wasserburg, G.J., 1994. ApJ 430, L77.
Choi, B.-G., Huss, G.R., Wasserburg, G.J., Gallino, R., 1998. Sci 282, 1284.
Choi, B.-G., Wasserburg, G.J., Huss, G.R., 1999. ApJ 522, L133.
Forestini, M., Paulus, G., Arnould, M., 1991. A&A 252, 597.
Hoppe, P., Besmehn, A., 2002. ApJ 576, L69.
Hoppe, P., Amari, S., Zinner, E., Lewis, R.S., 1995. Geochim. Cosmochim. Acta 59, 4029.
Hoppe, P., Strebel, R., Eberhardt, P., Amari, S., Lewis, R.S., 1996. Sci 272, 1314.
Hoppe, P., Strebel, R., Eberhardt, P., Amari, S., Lewis, R.S., 2000. Meteorit. Planet. Sci. 35, 1157.
Karakas, A.I., Lattanzio, J.C., 2003. PASA 20, 279.
Krestina, N., Hsu, W., Wasserburg, G.J., 2002. Lunar Planet. Sci. XXXIII (Abstract #1425).
Merrill, P.W., 1952. ApJ 116, 21.
Mowlavi, N., Meynet, G., 2000. A&A 361, 959.
Nguyen, A.N., Zinner, E., 2004. Sci 303, 1496.
Nittler, L.R., 2003. Earth Planet Sci. Lett. 209, 259.
Nittler, L.R. et al., 1995. ApJ 453, L25.
Nittler, L.R., Alexander, C.M.O'D., Gao, X., Walker, R.M., Zinner, E., 1997. ApJ 483, 475.
Nittler, L.R., Alexander, C.M.O'D., Stadermann, F.J., Zinner, E.K., 2005. Lunar Planet. Sci. XXXVI (Abstract #2200).
Nittler, L.R., Amari, S., Zinner, E., Woosley, S.E., Lewis, R.S., 1996. ApJ 462, L31.
Nollett, K.M., Busso, M., Wasserburg, G.J., 2003. ApJ 582, 1036.
Savina, M.R., Davis, A.M., Tripa, C.E., Pellin, M.J., Gallino, R., Lewis, R.S., Amari, S., 2004. Sci 303, 649.
Stadermann, F.J., Croat, T.K., Bernatowicz, T.J., Amari, S., Messenger, S., Walker, R.M., Zinner, E., 2005. Geochim. Cosmochim. Acta 69, 177.
Timmes, F.X., Woosley, S.E., Hartmann, D.H., Hoffman, R.D., 1996. ApJ 464, 332.
Travaglio, C., Gallino, R., Amari, S., Zinner, E., Woosley, S., Lewis, R.S., 1999. ApJ 510, 325.
Wasserburg, G.J., Boothroyd, A.I., Sackmann, I.-J., 1995. ApJ 447, L37.
Wasserburg, G.J., Busso, M., Gallino, R., Nollett, K.M., in press. Nucl. Phys. A.
Woosley, S.E., Weaver, T.A., 1995. ApJS 101, 181.
Zinner, E., 2004. In: Davis, A.M. (Ed.), Meteorites, Comets, and Planets. In: Holland, H.D., Turekian, K.K. (Eds.), Treatise on Geochemistry, vol. 1. Elsevier–Pergamon, Oxford, p. 17.
Zinner, E., Amari, S., Anders, E., Lewis, R.S., 1991. Nature 349, 51.
Zinner, E., Nittler, L.R., Hoppe, P., Gallino, R., Straniero, O., Alexander, C.M.O'D., 2005. Geochim. Cosmochim. Acta 69, 4149.