Mem. S.A.It. Vol. 75, 723

Memorie della

Constraints on AGB models

from the heavy-element composition of presolar SiC grains

M. Lugaro[1], A. M. Davis[2], R. Gallino[3], M. R. Savina[5], and M. J. Pellin[5]

[1] Institute of Astronomy, University of Cambridge, Madingley Rd, Cambridge CB3 0HA UK e-mail: mal@ast.cam.ac.uk
[2] Enrico Fermi Institute, Department of the Geophysical Sciences, and Chicago Center for Cosmochemistry, University of Chicago, Chicago, IL 60637, USA
[3] Dipartimento di Fisica Generale, Universitá di Torino, via P. Giuria 1, 10125 Torino, Italy
[4] Materials Science Division, Argonne National Laboratory, Argonne, IL 60439, USA

Abstract.
Presolar SiC grains formed around Asymptotic Giant Branch (AGB) stars during their carbon-rich phase and contain heavy elements in trace amounts showing the signature of the *slow* neutron capture process (*s* process). Thanks to recent advances in analysis techniques, SiC data now provide extremely precise information on neutron capture cross sections and AGB models. For example, high-precision data for Mo in single SiC grains indicate that a revision of the ^{95}Mo neutron capture cross section is needed, while data for Zr indicates that the ^{22}Ne(α,n)^{25}Mg reaction cannot be a dominant neutron source for the *s* process in AGB stars. We present model predictions for the composition of Fe-peak elements in AGB stars. These elements could be analysed in the near future thus providing further stringent constraints to our understanding of AGB stars.

Key words. nuclear reactions, nucleosynthesis, abundances – stars: AGB

1. Introduction

Among presolar meteoritic material, silicon carbide (SiC) grains have isotopic compositions very different to those commonly measured in the solar system. The majority of these grains are believed to have formed in the extended envelopes of carbon-rich Asymptotic Giant Branch (AGB) stars. A strong indication of this origin is the composition of elements heavier than Fe and present in very small amounts (*trace*), showing the unequivocal signature of the *slow* neutron capture process (*s*-process) that occurs in AGB stars (Gallino et al. 1998; Busso et al. 2001).

The bulk of *s*-process elements in AGB stars are produced when neutrons are released by the ^{13}C(α,n)^{16}O reaction. The ^{13}C neutron source is activated in a tiny region in the top layers of the He intershell, assuming that some small-scale mixing occurs between the H-rich convective envelope and the ^{12}C-rich He intershell at the end of each third dredge up. At H-reignition, proton captures on ^{12}C produce ^{13}C

Send offprint requests to: M. Lugaro
Correspondence to: Institute of Astronomy, University of Cambridge, Madingley Rd, Cambridge CB3 0HA UK

and a ^{13}C *pocket* is formed. The ^{13}C is subsequently consumed via (α,n) reactions, neutrons are released and *s*-process isotopes are overproduced by factors of up to several thousand times their initial abundances. The pocket is then engulfed in the convective zone driven by the thermal instability, and diluted by a factor of $\sim$ 1/20 with material from H-burning ashes and other He-intershell material.

During the thermal pulse a second small neutron exposure occurs, produced by the ^{22}Ne(α,n)^{25}Mg reaction, which is marginally activated at the bottom of the convective zone when the temperature reaches above 2.5×10^8 K. The marginal activation of the ^{22}Ne neutron source produces a small neutron burst of short duration ($\sim$ 6 yr) but with a high average peak neutron density, $\sim 10^{11}$n cm^{-3}, affecting the final composition of branching-dependent isotopes. After the quenching of the thermal pulse the following third dredge up episode mixes the *s*-processed material to the surface, where it is spectroscopically observed and it is included in SiC grains.

High-precision laboratory measurements of the isotopic compositions of SiC grains represent the most detailed record of the composition of AGB stars, and thus a major constraint for the theoretical models of these stars. In this paper we describe the technique used to analyse the composition of heavy elements in SiC grains (Section 2), a few main conclusions derived from comparing laboratory data to stellar models (Section 3) and predictions for the compositions in AGB envelopes of some Fe-peak elements (Section 4), which are good candidates for future high-precision measurements and will set further constraints to our knowledge of AGB stars.

2. The Chicago-Argonne Resonant Ionisation Spectrometer for Mass Analysis (CHARISMA)

To measure trace element compositions in single grains, instruments of very high sensitivity are needed to detect as much as possible of the low concentration of such elements. Moreover, for many heavy elements, isobaric *interferences* are present. This means that it is

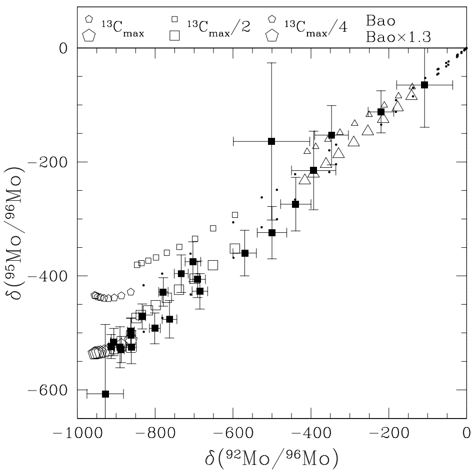

Fig. 1. Plot of the ^{95}Mo/^{96}Mo versus ^{92}Mo/^{96}Mo ratios (δ = permil variation with respect to solar) measured (black squares with 2σ errorbars) in single SiC and predicted (small dots and open symbols) by theoretical models at the surface of AGB stars of initial solar composition (δ=0 $^o/_{oo}$) and mass 1.5 $M_\odot$ for different choices of the amount of the ^{13}C neutron source. Each symbol in the predictions corresponds to a third dredge up episode. Open symbols represent situations in which C/O > 1 in the envelope, a necessary condition for the formation of SiC grains. The larger symbols for model predictions plot the same cases as the smaller symbols, except that the value of the ^{95}Mo(n,γ)^{96}Mo reaction has been multiplied by a factor of 1.3 with respect to the current recommended value.

not possible to distinguish between stable isobars, such as ^{96}Mo and ^{96}Zr.

In the mid-1990s a new instrument of high sensitivity was developed at the Argonne National Laboratory with which it is possible to analyse the composition of trace elements in single presolar grains of the relatively large size of a few μm (Ma et al. 1995; Savina et al. 2003b). This technique makes use of resonance ionisation mass spectrometry (RIMS). One or more lasers are tuned on the same energies needed to excite an atom to higher and higher energy levels, i.e. the lasers are in *resonance*

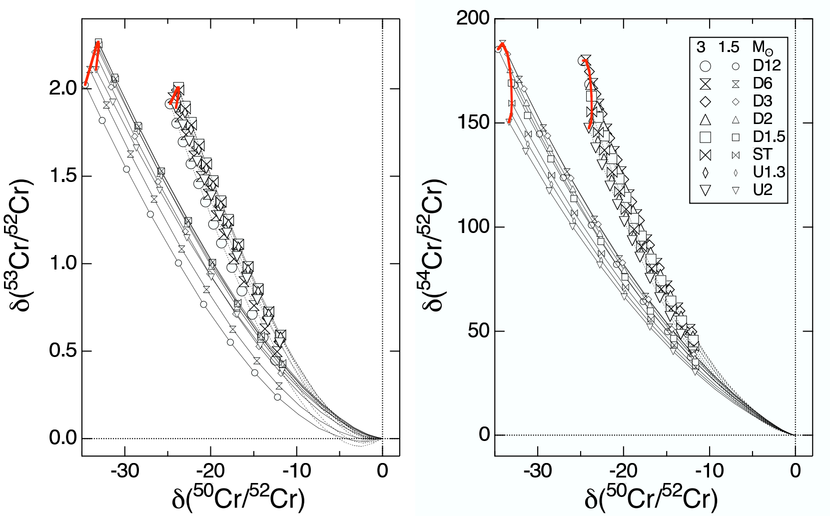

Fig. 2. Predicted isotopic composition of Cr.

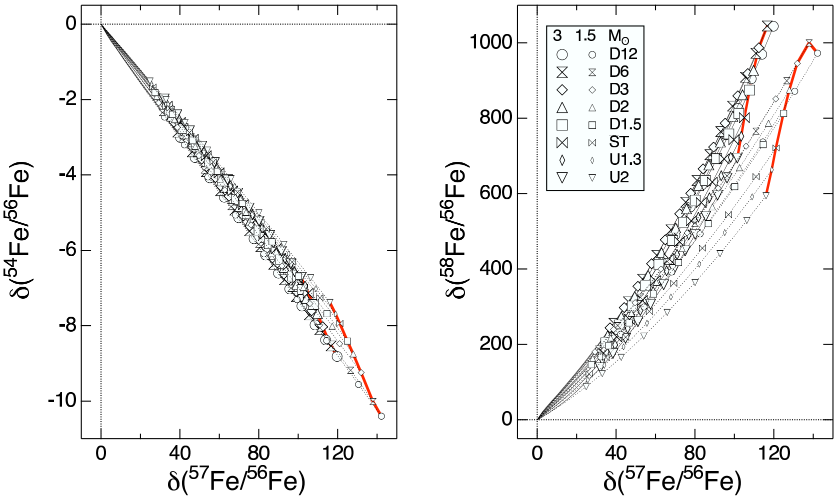

Fig. 3. Predicted isotopic composition of Fe.

with the atomic levels, until the energy of the atom is above its ionisation potential, electrons are freed and an ion is created. The extracted ions are then separated by mass by going through a Time-Of-Flight mass spectrometer, which separates different masses in time by using the differences in transit time of ions of different masses in an electric field. Once the ions are separated their number is analysed using a ion detector. Since each element has a unique energy level structure, RIMS provides an ionisation method that selects which element is going to be ionised and hence mass interferences are automatically avoided. Since this method must be applied to material in the gas phase, the solid grains are first vaporized by laser ablation. The RIMS technique has extremely high sensitivity so that enough ions are extracted even in the case of trace elements to allow a relatively precise measure of the isotopic composition of the element.

This technique has been applied to date to the measurement of Zr (Nicolussi et al. 1997), Mo (Nicolussi et al. 1998a), Sr (Nicolussi et al. 1998b), Ba (Savina et al. 2003a) and Ru (Savina et al. 2004) in single presolar large SiC and graphite grains (Nicolussi et al. 1998c) from the Murchison meteorite. These data are of invaluable significance in the study of the nucleosynthetic processes that produce the elements heavier than iron.

3. CHARISMA data and AGB stars

The implications for AGB models of data for Zr, Mo, Sr and Ba in single SiC have been studied in detail by Lugaro et al. (2003). One interesting example is the composition of ^{92}Mo, ^{95}Mo and ^{96}Mo shown in Figure 1 in the form of a three-isotope plot in which two isotopic ratios with a common reference isotope, ^{95}Mo/^{96}Mo and ^{92}Mo/^{96}Mo in this case, are plotted as function of one another. Three-isotope plots are widely used when comparing isotopic ratios because they have the helpful property that a composition resulting from the mixing of two types of *components* lies on a straight line connecting the points representing the two components. In the case of Figure 1, the data and the predicted values lay on a straight line connecting the component of solar composition (δ=0 $^o/_{oo}$) with the *s*-process component from the He intershell. Because ^{92}Mo is a *p*-only isotope, while ^{96}Mo is an *s*-only isotope $\delta(^{92}\mathrm{Mo}/^{96}\mathrm{Mo})_s = -1000\ ^o/_{oo}$ for the *s*-process component. Because $\sigma_n(A)N(A) \sim constant$ (where σ_n(A) is the neutron capture cross section, and $N(A)$ the abundance in number of a given isotope A) locally during the *s* process, $(^{95}\mathrm{Mo}/^{96}\mathrm{Mo})_s \simeq \sigma_n(^{96}\mathrm{Mo})/\sigma_n(^{95}\mathrm{Mo})$. Thus the slope of $\delta(^{95}\mathrm{Mo}/^{96}\mathrm{Mo})$ versus $\delta(^{92}\mathrm{Mo}/^{96}\mathrm{Mo})$ is an indication of the value of the neutron capture cross sections of these isotopes. The precision with which presolar grain data are obtained opens opportunities in predicting values of neutron capture cross sections thus stimulating new nuclear experiments. For example, SiC data for Mo isotopes are best matched when increasing by 30% the value of the ^{95}Mo(n,γ)^{96}Mo reaction recommended by Bao et al. (2000). Cross sections of Mo, and Zr, isotopes are known with a considerable uncertainty and more precise measurements are highly desirable.

When analysing the Zr composition of single SiC (see Figure 5 of Lugaro et al. 2003), it is easy to see that the mixing lines in the three isotope plots are far from being straight lines. This means that the *s*-process component from the He intershell of AGB star is not constant. A wealth of precise of information can be thus derived on AGB models. First, ^{90,91,92}Zr have or are close to having a magic number of neutrons. Their neutron capture cross sections are very low, so their production is very sensitive to the main neutron exposure in the ^{13}C pocket. The spread in the ^{90,91,92}Zr/^{94}Zr ratio observed in single presolar SiC grains is matched only by allowing a spread of efficiencies in the neutron flux in the ^{13}C pocket. On the other hand, ^{96}Zr is produced via a branching at the unstable ^{95}Zr only if the neutron density exceeds $\simeq 5 \times 10^8$ neutrons/cm^3. Data from single SiC grains show deficits in the ^{96}Zr/^{94}Zr ratio with respect to solar and point to a marginal activation of ^{22}Ne neutron source in the grain parent stars.

4. A future opportunity: the Fe-peak elements

The Galactic production of elements belonging to the Fe peak is due to the operation of the *equilibrium* process in supernovae. These elements are not produced by the *s*-process, however, their isotopic composition in AGB stars can be modified by neutron captures. Because of their high solar abundances and low neutron capture cross sections, modifications to the compositions of Fe-peak isotopes in AGB stars are mostly due to the activation of the ^{22}Ne neutron source in the convective thermal pulse. In Figures 2, 3 and 4 we present the predicted composition of Cr, Fe and Ni isotopes at the surface of AGB models of 1.5 and 3 M$_\odot$ and solar metallicity for different choices of the ^{13}C amount in the ^{13}C pocket. As in Figure 1, δ represents the permil variation with respect to

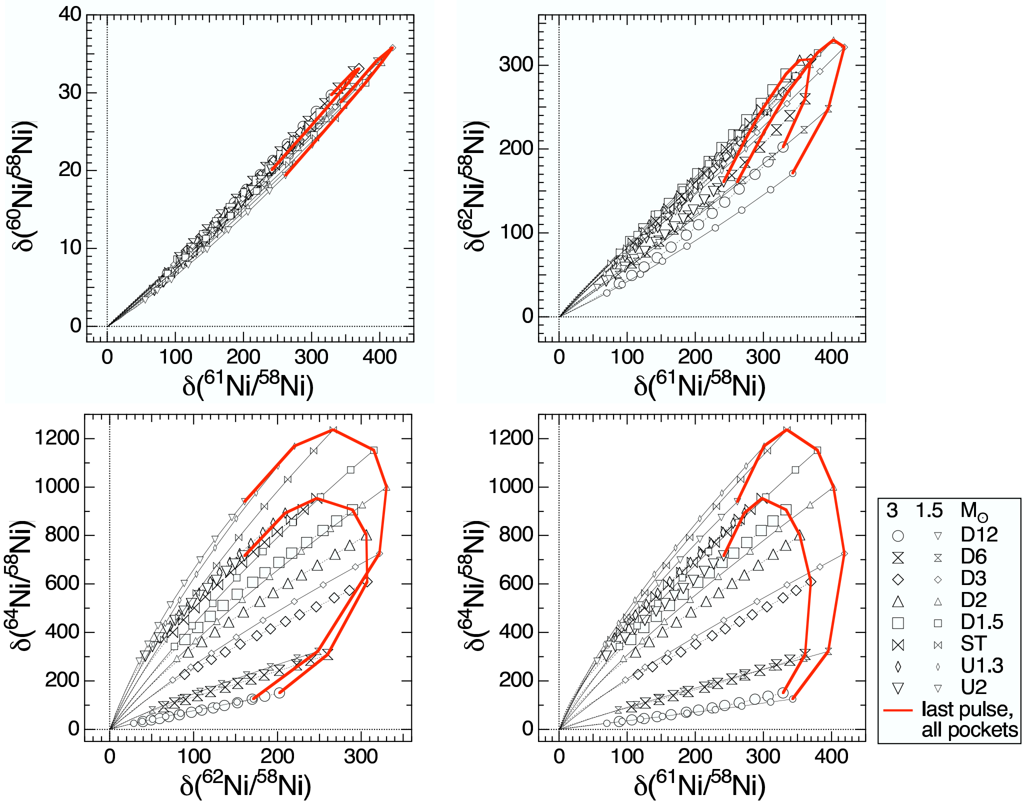

Fig. 4. Predicted isotopic composition of Ni.

solar and open symbols are used when C/O>1. The points representing the final composition for each ^{13}C pocket case of a given mass are connected by a thick solid line. As for the Cr isotopic composition, only the ^{54}Cr/^{52}Cr ratio is significantly modified by nucleosynthesis in AGB stars, increasing by up to 20% of its solar value.

Among the Fe isotopic ratios, ^{58}Fe/^{56}Fe stands out reaching up to twice the solar value. Because of the very low abundance of ^{58}Fe (0.28% of Fe in the solar system) it is a challenge to measure this isotopic ratio in SiC. If this task is accomplished, strong constraints will be set on the operation of the ^{22}Ne neutron source in AGB stars, which is mostly responsible for the increase of the ^{58}Fe/^{56}Fe ratio. Another isotopic ratio of much interest is represented by the ^{64}Ni/^{58}Ni ratio. As shown in Figure 4, unlike the other Fe-peak isotopic ratios presented here, the ^{64}Ni/^{58}Ni ratio varies greatly with the choice of the ^{13}C amount in the pocket, ranging from 20% to more than factor of two of its solar value. Measurements of this ratio will represent further indications of the features of the neutron flux in the ^{13}C pocket, in particular they could confirm, or maybe not, the fact that a spread of *s*-process efficiencies occurs in the ^{13}C pocket. We also note that the composition of Fe-peak element depends on the choice of mass loss used to compute the AGB models and thus could represent a way to better constrain this uncertain parameter of AGB evolution.

The composition of Fe-peak elements can also be affected by the initial composition of the star and thus measurements of such composition could set detailed constraints on the Galactic chemical evolution of isotopes of these elements. As measurement techniques improve fast with modern technology the opportunities coming from the study of presolar grains are compelling and cannot be ignored in the future of AGB modelling.

Acknowledgements. This research was supported by the IoA PPARC rolling grant, the National Aeronautics and Space Administration, the Italian MIUR-FIRB Project "Astrophysical origin of the heavy elements beyond iron" and the Department of Energy, BES-Material Sciences through Contract No. W-31-109-ENG-38.

References

Bao Z. Y., et al., 2000, Atom. Data Nucl. Data Tables, 75, 70
Busso M., et al., 2001, ApJ, 557, 802
Gallino R., et al., 1998, ApJ, 497, 388
Lugaro M., et al., 2003, ApJ, 593, 486
Ma Z., et al., 1995, Review of Scientific Instruments, 66, 3168
Nicolussi G. K., et al., 1997, Science, 277, 1281
Nicolussi G. K., et al., 1998a, Geochim. Cosmochim. Acta, 62, 1093
Nicolussi G. K., et al., 1998b, Phys. Rev. Lett., 81, 3583
Nicolussi G. K., et al., 1998c, ApJ, 504, 492
Savina M. R., et al., 2003a, Geochim. Cosmochim. Acta, 67, 3201
Savina M. R., et al., 2003b, Geochim. Cosmochim. Acta, 67, 3215
Savina M. R., et al., 2004, Science, 303, 649