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Stellar origin of the meteoritic Xe-S anomalous component

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Abstract. The meteoritic Xe-S isotopic composition carried by presolar SiC grains is compared with stellar evolutionary and nucleosynthesis predictions for carbon stars. Very precise neutron capture cross sections have been recently measured and have been used in an extended nuclear network to follow in detail the *s*-process nucleosynthesis occurring in asymptotic giant branch stars (AGB). Excellent agreement between the meteoritic pure-*s* xenon component (the Xe-G component) and the results of stellar models is reached for AGBs of low initial mass and with metallicities from solar to half-solar. AGB stars of lower metallicity would produce excesses of ^{134}Xe/^{130}Xe with respect to the Xe-G component. For the same reason, also the alternative hypothesis of implantation of ionized xenon in the planetary nebula phase from the central star into SiC grains present in the planetary nebula is ruled out.

1. Introduction

The Solar System is the result of collapse of a cloud made of interstellar gas and dust. Presolar grains were trapped and survived in primitive meteorites, and carry the signature of the nuclear processes that were active in the parent stars. Carbonaceous meteorites contain a few ppm of presolar silicon carbide (SiC) grains (Zinner et al. 1998). Mainstream SiC grains (Zinner et al. 1998) constitute more than 90% of presolar SiC; they form in the cool mass-losing envelopes of asymptotic giant branch (AGB) stars when the envelope becomes C-rich (C/O > 1). The C-stars of type N show spectroscopic evidence of *s*-element enrichments. Mainstream SiC grains have been shown to be the carriers of the anomalous meteoritic Xe-S component, which is strongly enriched with *s*-process Xe. Of the nine stable xenon isotopes, ^{124,126}Xe are *p*-only isotopes, ^{128,130}Xe are *s*-only isotopes, ^{129,131,132}Xe are of mixed *s*- and *r*-process origin, and the most neutron-rich ^{134,136}Xe are *r*-only isotopes.

High precision mass spectrometric analyses (Lewis et al 1990; Lewis et al. 1994) showed that the Xe isotopic composition in SiC grains is a mixture of two components, a pure-*s* component (Xe-G), free of the *p*-only

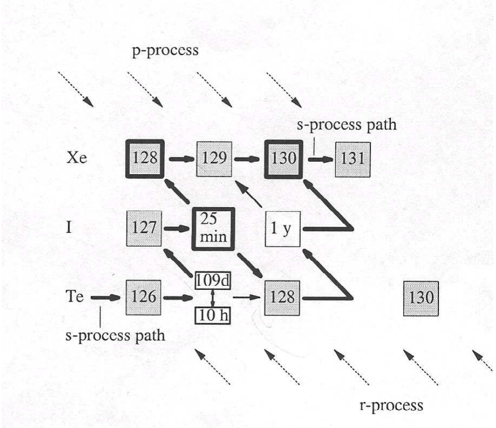

Fig. 1. The s-process path in the Te-I-Xe region. The abundances of the two s-only isotopes ^{128,130}Xe are affected by the branchings at ^{128}I and ^{127}Te. The branching at ^{128}I is unique, since it results from the competition between β^- and electron capture decays and is, therefore, independent of the neutron flux.

and r-only isotopes and a normal component (Xe-N) close to solar.

Since very precise measurements of neutron capture cross sections of Xe isotopes have been recently obtained by Reifarth et al. (2002), with uncertainties at 1σ of 2% for ^{128,129,130}Xe, one has the opportunity to challenge theories of stellar evolution and nucleosynthesis for AGB stars at an unprecedented level of accuracy.

2. The s-Process

The s-process path in the Te-I-Xe region is shown in Fig. 1. In AGB stars, this process is active in the He intershell, which is a thin region between the H shell and the He shell. Recurrent thermal instabilities in the He shell drive the whole intershell to become convective for a short period of time (thermal pulse, TP) and the H-burning shell to be temporarily inactive. After a limited number of TPs, at the quenching of each thermal instability, the convective envelope penetrates into the He intershell. Newly synthesized ^{12}C and s-rich material are mixed into the envelope (third dredge up phenomenon, TDU). As far as the s-process is concerned, there are two neutron sources, which operate under different conditions (Gallino et al. 1998):

1. The reaction ^{13}C(α, n)^{16}O takes place in the radiative interpulse phase at a temperature of $\sim 1 \times 10^8$ K. The amount of ^{13}C left behind by the H-burning shell is too low to induce a significant s-process production. However, as a consequence of TDU, a small amount of protons penetrate from the H-rich envelope into the top layers of He-intershell immediately after each TDU. At H reignition, protons are captured by the abundant ^{12}C, so that a thin ^{13}C *pocket* is formed via the sequence ^{12}C(p, γ)^{13}N($\beta^+\nu$)^{13}C. During ^{13}C consumption, the neutron density reaches 10^7 cm^{-3} and the s-process follows the β-decay path at branch points. The exact amount of the mass fraction of ^{13}C and of its abundance profile in the pocket cannot be predicted on physical principles in a strict quantitative way. Actually, a large spread of ^{13}C pocket efficiencies is required for reproducing the spectroscopic observations of s-enhanced stars at a given metallicity (Busso et al. 2001; Abia et al. 2001);

2. The reaction ^{22}Ne(α, n)^{25}Mg occurs during the development of a TP. A large abundance of ^{22}Ne results in the He intershell as a consequence first of the conversion of all CNO nuclei to ^{14}N in the H-burning shell, then by double α-capture on ^{14}N during the early development of the next convective TP. Despite its large abundance, the ^{22}Ne neutron source is only marginally activated in low-mass AGB stars, since the maximum temperature in the bottom layers of the pulse barely reaches 3×10^8 K. This maximum temperature increases slightly with pulse number and is sensitive to the initial mass and metallicity, reaching $\sim 3.5 \times 10^8$ K in the more massive AGB stars. On the whole, during the convective pulse the ^{22}Ne abundance is modestly depleted by α captures. The ^{22}Ne neutron source induces a peak neutron density of 5×10^9 to 10^{11} cm^{-3}, depending on the AGB mass and metallicity. Although the corresponding neutron exposure $\tau = \int n_n v dt$ is low, it affects the final abundances induced by branchings along the s-path.

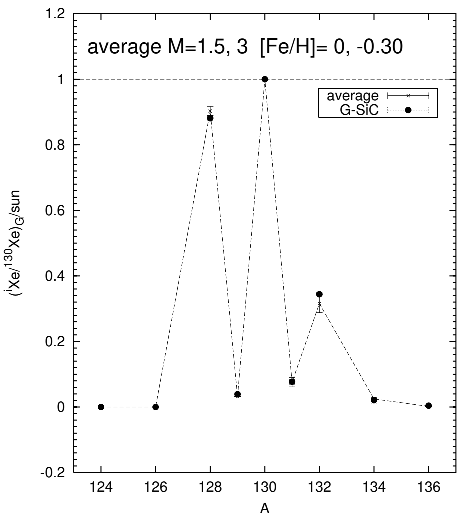

Fig. 2. Envelope Xe-G component from AGB models for solar and half-solar metallicities compared with the Xe-G component of presolar SiC grains.

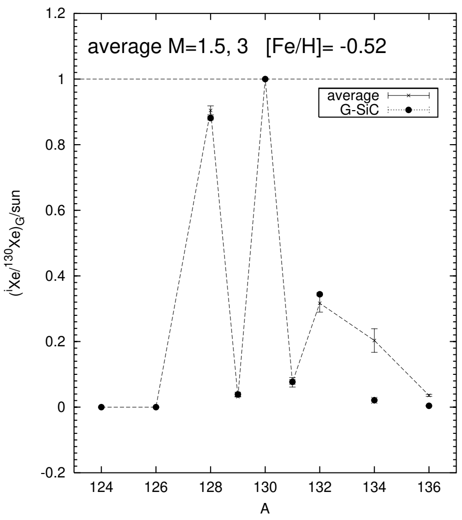

Fig. 3. Envelope Xe-G component from AGB models for 1/3 × solar metallicity compared with the Xe-G component of mainsteam SiC.

3. Data analysis

Figure 2 compares the meteoritic Xe-G isotopic component (Lewis et al. 1994), normalized to the *s*-only isotope ^{130}Xe and to solar abundances (Wieler 2002), with AGB model predictions for pure He-intershell material cumulatively mixed with the envelope by the various TDU episodes. The theoretical predictions are for a "*grand weighted-mass average*" that covers all envelope conditions with C/O > 1, a wide range of ^{13}C-pockets as required by spectroscopic observations, the range of metallicity from solar to half-solar, and the range of mass between 1.5 and 3 $M_{\odot}$. Excellent agreement is found in all Xe isotope ratios within the 1σ uncertainty. In particular, the predicted ratio to solar of the $s-only$ pair ^{128}Xe/^{130}Xe is close to 0.9, practically coincident with the ratio given by the meteoritic Xe-G component. This result is established in freezout conditions during the sharp decrease of the neutron density when the temperature at the bottom of the convective pulse declines.

The above deficit by 10% of ^{128}Xe/^{130}Xe with respect to solar is attributable to an extra 10% *p*-process contribution to solar ^{128}Xe. In fact, the two *p*-only isotopes ^{124,126}Xe amount to 0.1% of solar xenon each, which corresponds to ∼5% of solar ^{128}Xe, and it is likely that ^{128}Xe also has a *p*-contribution of this magnitude. The overall match obtained between the measured meteoritic Xe-G component and accurate AGB stellar model nucleosynthesis results, using very precise neutron capture cross sections of Xe isotopes, constitutes a unique synergy of different fields of research, providing also robust constraints to the still debated origin of the rare *p*-process isotopes.

At lower metallicities, ^{134}Xe is significantly overproduced by the models with respect to meteoritic Xe-G data, as is shown in Fig. 3 for the case of a 1/3 solar metallicity. This derives from the somewhat higher temperature in the bottom of the convective thermal pulse, which causes the neutron capture channel at unstable ^{133}Xe ($t_{1/2}$ = 5.25 d) to marginally feed ^{134}Xe at the peak neutron density driven by the ^{22}Ne neutron source. This oc-

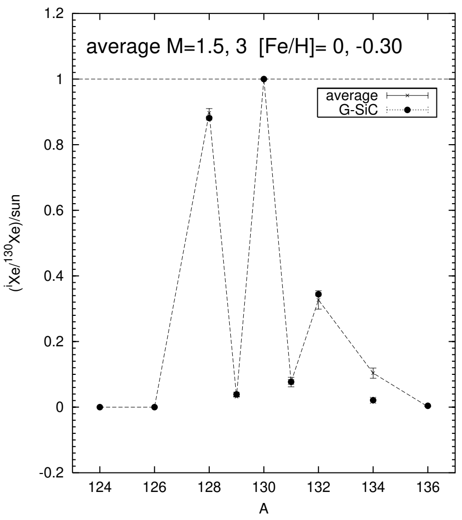

Fig. 4. Pure He intershell Xenon isotopic composition from AGB models for solar and half-solar metallicities compared with the Xe-G component of presolar SiC grains.

curs in particular in the 3 $M_\odot$ model of 1/3 solar metallicity, where n_n in the advanced TPs reaches a peak value of 5×10^{11} cm^{-3}. In the 3 $M_\odot$ AGB model of solar to half-solar metallicity the peak neutron density reaches 1×10^{10} cm^{-3}. As for the 1.5 $M_\odot$ AGB models at the various metallicities, n_n reaches 5×10^9 cm^{-3}. In those conditions, the neutron channel at ^{133}Xe is almost closed.

A similar negative result is obtained under the alternative hypothesis of implantation of ionized xenon into SiC by hot stellar winds from the central star during the subsequent planetary nebula phase. Here, theoretical predictions shown in Fig. 4 have been obtained by considering the pure He-shell Xe composition after the last TP and then making the grand weighted average over initial masses, metallicities, and ^{13}C-pockets.

4. Conclusions

Very good agreement with Xe-G component in meteoritic presolar SiC grains is found compared with AGB models of solar and half-solar metallicities in which xenon atoms are trapped in SiC grains in the AGB mass-losing envelopes. Lower metallicities are excluded because of the too high predicted ^{134}Xe. The same is true for the alternative hypothesis of implantation of ionized Xe from pure He shell material of the central star in the planetary nebula phase.

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