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The origin of xenon trapped in presolar mainstream SiC grains

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Abstract. We present an analysis of the origin of the Xe-*S* component implanted in mainstream presolar SiC grains considering two different scenarios: the first one assumes that xenon is implanted in the grains by cool and partly ionized winds during the AGB phase of carbon stars; the second one assumes that xenon is implanted in the subsequent planetary-nebula phase by hot and strong ionized winds from the central star. A comparison of AGB nucleosynthesis models predictions with measurements in bulk SiC grains is presented. This shows that ^{134}Xe, an *r*-only isotope with a small *s*-contribution sensitive to the neutron channel branching at the unstable ^{133}Xe, is a major indicator in favour of the first implantation scenario. This also constrains the mass and the metallicity of the parent AGB stars.

1. Introduction

Presolar mainstream SiC grains are present in pristine carbonaceous meteorites in few parts per million. They are the carriers of anomalous noble gases, in particular the Kr-*S* and of the Xe-*S* component (see Lewis, Amari & Anders 1990; Lewis, Amari & Anders 1994; references therein). Mainstream SiC grains originate in the mass-losing envelope of carbon stars (type N), which represent the most advanced phases of asymptotic giant branch (AGB) stars of low initial mass ($1.5 - 3\,M_{\odot}$) (Gallino et al. 1990; Gallino, Busso & Lugaro 1997).

For Xe, two main components were extrapolated by measurements on a very large sample of grains ($10^5 - 10^6$ grains, Lewis, Amari & Anders 1994), a normal, close to solar, component (N component) and an anomalous one, the Xe-*S* component. In this paper we analyse the astrophysical origin of the Xe-*S* component. In particular we want to analyse under what conditions noble gas Xe ions are implanted in SiC grains. Recalling that on average very few Xe atoms are present per SiC grain, we may have two possible scenarios for Xe implantation. In the first scenario Xe ions are implanted during the growth of SiC grains in the mass losing envelopes of AGB stars when $(C/O)_{env} > 1$. In this case the Xe isotopic ratio corresponds to the average Xe composition of the stellar envelope (cold wind). In the second scenario, Xe is implanted as a hot ionized wind from the

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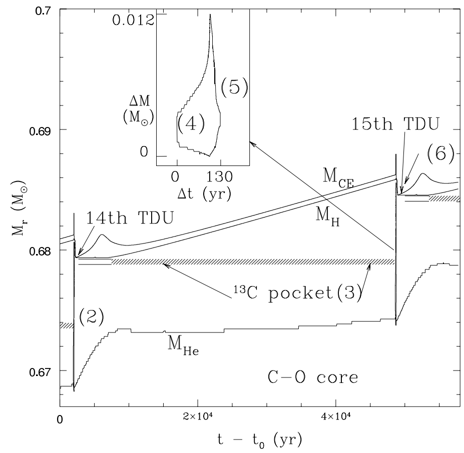

Fig. 1. Schematic evolution for an AGB star of 1.5 $M_{\odot}$ and solar metallicity between 14th and 15th pulse with TDU. The mass coordinate is plotted against time (Kahane et al. 2000).

central star of a planetary nebula on to the SiC grains previously formed during the late AGB phases and still present in the nebula. In this case, the ionized gas is made of pure Xe-*S* material. One may notice that spectroscopic observations confirm the presence of ionized Kr in emission in PN NGC7027 (Dinerstein 2004; references therein). However previously hinted at observations of Xe in emission lines have not been confirmed. A common condition for both implantation scenarios is that Xe must be ionized before being implanted in the grains (Verchovsky, Wright & Pillinger 2004). In section 2 we briefly describe the *s*-process nucleosynthesis occurring in AGB stars. In section 3 we discuss the Xe-*S* component in mainstream SiC grains. In sections 4 and 5 we compare the Xe-*S* component with our AGB nucleosynthesis models and the role played by ^{134}Xe as an indicator of the initial mass and metallicity of the parent AGB stars. In section 6 we present the main conclusions of this study.

2. AGB stars and the *s*-process

As shown in Figure 1, during the AGB phase the star is made of a core of carbon and oxygen, a thin region of about 0.01 $M_{\odot}$ (the one shown in Figure 1) which comprises the He-shell, the He-rich and C-rich intershell region (He intershell) and the H shell, and an extended convective envelope. The ignition of the 3α reaction (3 $\alpha \rightarrow$ ^{12}C) in the He shell occurs episodically in quasi-explosive conditions during a thermal instability (thermal pulse, TP), when the whole He intershell becomes convective for a short period of time. After a limited number of thermal pulses, after the quenching of the TP, the H shell is inactive and the convective envelope penetrates the upper layers of the He intershell (third dredge-up event, TDU), mixing with the surface newly synthesized ^{12}C and *s*-process material from the He intershell. During a TDU a sharp chemical discontinuity is produced between the H-rich convective envelope and the C-rich He intershell. In this situation the penetration of a small number of protons into the upper layers of the He intershell is to be expected. At H reignition proton captures on the abundant ^{12}C give rise to the formation of a thin ^{13}C pocket (Straniero et al. 1997; Gallino et al. 1998). This region is further compressed and heated. At $T \approx 0.9 \times 10^8$ K, the reaction ^{13}C(α,n)^{16}O consumes the ^{13}C nuclei in radiative conditions before the growth of the next convective TP. This reaction is the major neutron source for the build up of the *s*-process in AGB stars.

During the next TP, the *s*-process isotopes are mixed with the whole He intershell and subsequently partly brought to the surface by the next TDU. In a thermal pulse the ^{22}Ne(α,n)^{25}Mg reaction is marginally activated generating a short neutron burst of high neutron density ($n_{\rm n} \approx 10^{11}$ cm^{-3}). The neutron exposure induced by the ^{22}Ne neutron source is small but there are important effects on the *s*-process yields for isotopes involved in branchings that depend on the neutron density. In summary in the advanced stages of an AGB star's evolution we may separate two different Xe components in the envelope. The first is made of the original composition present in the interstellar medium from which the star condensed (N component) and a second made of pure *s*-process material mixed with the envelope by all previous TDU episodes (G component).

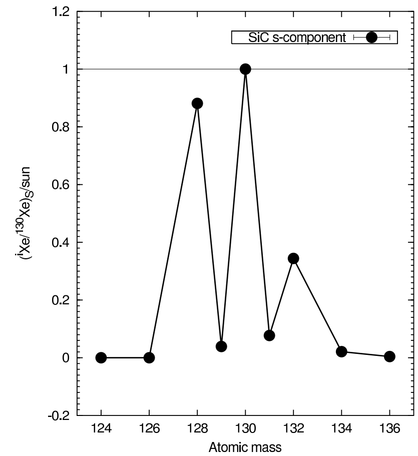

Fig. 2. Xe-*S* isotopic ratios extrapolated from measurements on a large sample of SiC grains (Lewis, Amari & Anders 1994).

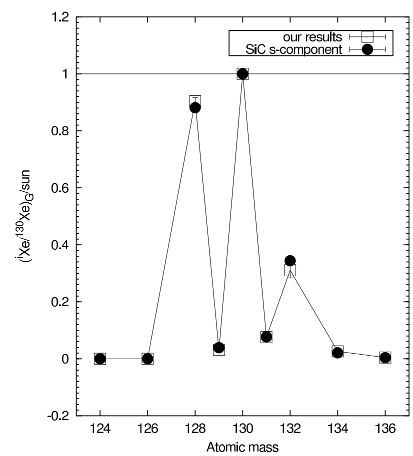

Fig. 3. Xe-*S* isotopic ratios from mainstream SiC (black circles) plotted against our predictions for the G component (open squares). Predictions are weighted mass averages over AGB models of different initial stellar mass, metallicityb and ^{13}C-pockets. For each AGB model average abundances in the winds with $(C/O)_{env} > 1$ are considered.

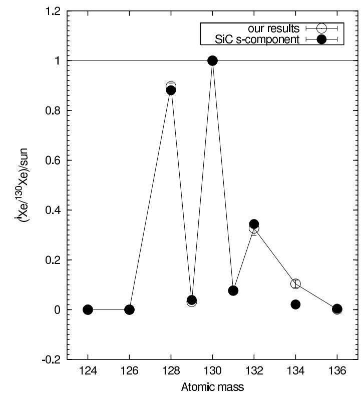

Fig. 4. Xe-*S* isotopic ratios from mainstream SiC (black circles) plotted against our predictions for pure He-intershell abundances (open squares). Predictions are weighted mass averages over AGB models of different initial stellar mass, metallicity and ^{13}C-pockets. For each AGB model abundances in the He intershell after the last thermal pulse are considered.

3. Xe-*S* in mainstream SiC

In Figure 2 the Xe isotopic ratios with respect to solar abundances are plotted for the *s*-component extrapolated by Lewis, Amari & Anders (1994). The lightest ^{124}Xe and ^{126}Xe are *p*-only isotopes, which are bypassed by the *s*-fluence. Their initial abundance in the He intershell is destroyed during the *s*-process owing to their large neutron capture cross section. The pair ^{128}Xe and ^{130}Xe are *s*-only isotopes, shielded against the *r*-process by the respective stable isobars ^{128}Te and ^{130}Te. As seen in Figure 2, the (^{128}Xe/^{130}Xe)-*S* ratio is about 0.9 times solar, both in the Xe-*S* component extracted for mainstream SiC grains and in accordance with our AGB predictions.

A typical *s*-process odd–even pattern is seen in Figure 2 for the $^{128-132}$Xe isotopes which mostly reflect the inverse ratio of the *s*-process isotope abundance with its neutron capture cross section. The neutron-rich isotopes ^{134}Xe and ^{136}Xe are *r*-only isotopes, typically bypassed by the *s*-process. This explains why these two isotopes are absent in the Xe-*S* component, analogous to the *p*-only light isotope pair ^{124,126}Xe. Actually closer scrutiny reveals that there is evidence of a small amount of ^{134}Xe of *s*-origin: [^{134}Xe/^{130}Xe]-$S = 0.046 \pm 0.018$.

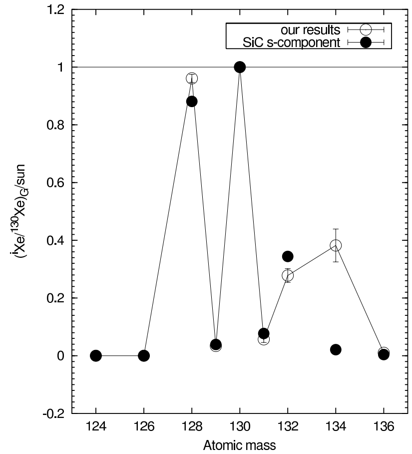

Fig. 5. Xe-*S* isotopic ratios in mainstream SiC (black circles) plotted against our G component predictions for AGB models of $M = 5\,M_\odot$ and solar metallicity (open squares).

4. Comparison of Xe-*S* in SiC grains and AGB models

To distinguish between the two implantation scenarios discussed in the introduction, we make a comparison of the Xe-*S* component in SiC grains with our predictions with AGB models. In Figure 3 we report our predictions for the G component in the envelope. The results are weighted mass averages over predictions from AGB models with different ^{13}C-pockets (from 2ST to ST/2, Arlandini et al. 1999), metallicities ($Z_\odot$ and $Z_\odot/2$) and initial masses (1.5 and $3\,M_\odot$). For each AGB model, we made a mass average of the abundances present in the winds only at $(C/O)_{env} > 1$. Within one standard deviation, these results match the SiC Xe-*S* component in SiC grains well. The nice agreement between the meteoritic ^{128}Xe/^{130}Xe ratio and AGB model predictions indicates that about 10% of solar ^{128}Xe is actually to be ascribed to the *p*-process (Reifarth et al. 2004). The match extends to the small amont of *s*-process ^{134}Xe. Indeed this isotope can be manufactured via the neutron-branching channel at the unstable ^{133}Xe. This occurs during the neutron density peak induced by the ^{22}Ne neutron source which is marginally activated in a convective TP.

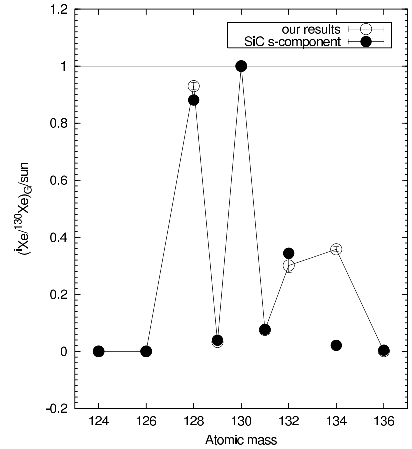

Fig. 6. Xe-*S* isotopic ratios in mainstream grains (black circles) plotted against our predictions for the G component (open squares). Predictions are weighted mass averages over AGB models of $3\,M_\odot$ initial stellar mass, 1/3 solar metallicity and different ^{13}C-pockets. For each AGB model average abundances in the winds with $(C/O)_{env} > 1$ are considered.

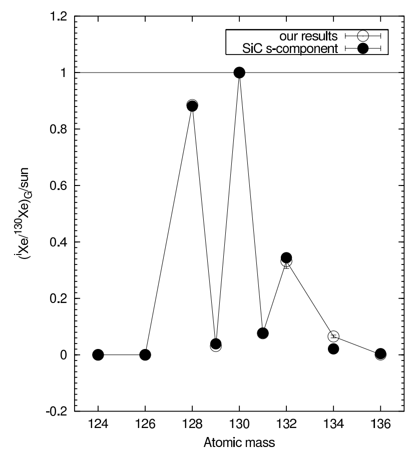

Fig. 7. Xe-*S* isotopic ratios in mainstream grains (black circles) plotted against our predictions for the G component (open squares). Predictions are weighted mass averages over AGB models of $1.5\,M_\odot$ initial stellar mass, 1/6 of solar metallicity and different ^{13}C-pockets. For each AGB model, average abundances in the winds with $(C/O)_{env} > 1$ are considered.

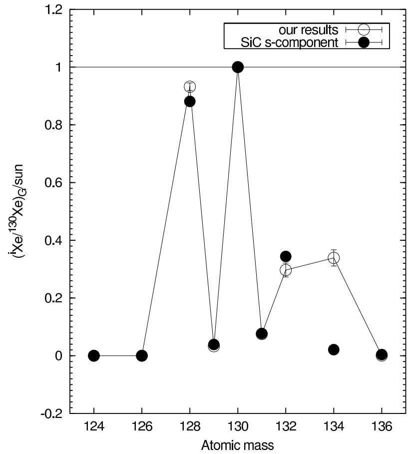

Fig. 8. The same as Figure 7, but for AGB models of initial stellar mass $M = 3\,M_{\odot}$.

In Figure 4 the Xe-S component of mainstream SiC grains is plotted against our predictions of pure He-intershell abundances, with the same averages as in the previous case but for the abundances in the He intershell after the last TP, in accord with the second scenario discussed in the introduction. The results match the SiC Xe-S component except for [^{134}Xe/^{130}Xe]-S ratio. Indeed the ^{134}Xe/^{130}Xe predicted for the pure He intershell component is too high when compared with the Xe-S component in mainstream SiC. We deduce that the (^{134}Xe/^{130}Xe)-S ratio is a strong indicator of the Xe-S origin: the Xe-S in SiC grains is likely implanted directly from the envelope during a cold wind. If some Xe ions are implanted in the SiC grains by the hot wind in the PN phase their contribution to the Xe-S component is negligible.

5. ^{134}Xe as indicator of the initial mass and metallicity of parent AGB stars.

The extrapolated (^{134}Xe/^{130}Xe)-S ratio may be used as an indicator of the average metallicity and mass range of the parent AGB stars. First indications were presented by Pignatari et al. (2004). In Figure 5 the Xe-S component in mainstream SiC grains is plotted against the envelope G component predicted for an AGB model of $5\,M_{\odot}$ and solar metallicity. In Figure 6, we report the predictions for the G component of AGB models of initial mass $M = 3\,M_{\odot}$ and 1/3 solar metallicity. In Figure 7, the corresponding predictions for an AGB model of initial mass $M = 1.5\,M_{\odot}$ and 1/6 of solar metallicity are reported and in Figure 8 those for an AGB model of initial mass $M = 3\,M_{\odot}$ and 1/6 of solar metallicity. In each case the predicted (^{134}Xe/^{130}Xe)-G is too high with respect to the Xe-S extracted from mainstream SiC grains. The ^{134}Xe production is sensitive to the peak neutron density released by the ^{22}Ne neutron source during a TP. For AGB stars of higher initial mass or lower metallicity the maxinum temperature reached in the bottom layers of a convective TP is higher and consequently the ^{22}Ne neutron source is more efficient. The above considerations constrain the parent AGB stars of the bulk of mainstream presolar SiC grains to be of low mass and of close to solar metallicity.

6. Conclusions

The extrapolated (^{134}Xe/^{130}Xe)-S ratio from a large sample of presolar mainstream SiC grains is a strong indicator of the implantation mechanism of the Xe-S in the grains. In particular the (^{134}Xe/^{130}Xe)-S ratio predicted by AGB models for the pure He intershell component is too high, while the predictions for the G component in the envelope are in agreement with the Xe-S measured in mainstream SiC grains.

The production ratio (^{130}Xe/^{82}Kr)$_S$ predicted by AGB stars is comparable with the solar ratio of 0.037 (Lodders 2003). An opposite trend is actually shown by the grains (Lewis, Amari & Anders 1990), a strong argument in favour of a chemical fractionation between Xe and Kr in the ionised winds. Neon is even more fractionated: SiC grains are indeed the carriers of the anomalous meteoritic Ne-E(H) component, made of almost pure ^{22}Ne. Most of the Ne is implanted in SiC grains by hot ionised winds in the planetary-nebula phase. It is gratifying that our results are in agreement with the independent theoretical predictions of Verchovsky, Wright & Pillinger (2004; see also these proceedings). These predictions are based on geometrical implantation models for SiC grains of various sizes and on the kinetic energy of the implanted ions. The (^{134}Xe/^{130}Xe)-S ratio is an indicator of the range of metallicity and initial mass of AGB stars that provided the bulk of SiC grains present in the protosolar nebula. For intermediate-mass AGB models of solar metallicity such as the $M = 5\,M_\odot$ discussed in the previous section or the $M = 3\,M_\odot$ models with metallicity lower than $1/3\,Z_\odot$ the predicted ^{134}Xe ratio is too high. The same is true for AGB stars of mass $M = 1.5\,M_\odot$ and metallicity below 1/6 solar.

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