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Physical parameters of AGB winds derived from the implanted species in meteoritic SiC grains

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Abstract. SiC grains, found in meteorites, condensed in the atmospheres of carbon-rich AGB stars contain implanted species such as noble gases, Ba and Sr acquired at different stages of stellar evolution. Analysis of the implantation effects in the grains allows the calculation of implantation energies for the species and constrains the implantation scenario. This puts some limits on the physical parameters of AGB winds. The results are discussed in connection with the existing AGB wind theories.

Key words. Stellar wind – AGB stars – presolar grains

1. Introduction

Recently it has been shown (Verchovsky et al. 2004) that variations in noble gas concentrations found in meteoritic SiC grains of different sizes (Lewis et al. 1994) can be simply explained as a result of implantation. The implantation has occurred in the envelopes of AGB stars and involved both isotopically normal (close to solar composition) and *s*-process components generated during the third dredge-up stage of evolution. Simple theoretical models developed for implantation in free space (Verchovsky et al. 2003) have allowed calculation of implantation energies for different noble gas species present in SiC grains. Analysis of the calculated energies suggests that there are several energetically different components for both isotopically normal and *s*-process noble gases. In particular the *s*-process noble gases generated at low and high neutron densities, the presence of which is revealed by the relative abundance of ^{86}Kr (sensitive to neutron density because of the branching point at ^{85}Kr in the *s*-process path), have significantly different energies. This points to a complicated implantation scenario which involves several independent events.

2. Implantation scenario

Two significantly different energies found for the noble gas components in SiC grains require different physical processes and environments. Below the results of Verchovsky et al. (2004) are summarised.

2.1. The low energy component

It is assumed that the low energy component has been implanted during the main stage of AGB evolution and involves both isotopically normal and *s*-process species present in the

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AGB envelope. Its energy (≤1 keV nucleon^{-1}) corresponds with the range observed for the AGB winds (10-30 km s^{-1}) during the main stage of envelope expansion. This component is thought to include all noble gases but, in fact, Xe dominates over the other noble gases, so that, apart from Xe, only the low energy Kr component can be detected. This apparent element fractionation in the envelope gas was noticed first by Lewis et al. (1994) (Figure 1) and appears to be caused by partial ionisation that occurred at relatively low temperatures (the typical effective temperature of AGB stars during their main stage of evolution is ~3000K). This also means that only ionised atoms can be implanted into SiC grains in spite of the quite low ionisation efficiency at the ambient envelope temperature. For instance, at 3000K only $\sim 10^{-21}$ of all Xe atoms will be ionised. The neutral atoms, which dominate in the envelope, do not participate in the implantation process at all.

Because of their chemical inertness, noble gases are not practically trapped into SiC grains during their growth and therefore implantation into solid grains is the only mechanism by which the elements can be acquired. Apart from noble gases, few other elements also have a noticeable contribution due to implantation. These are elements with relatively low first ionisation potentials such as alkaline-earth elements. The experimental observations suggest that of all the Ba and Sr present in SiC grains, up to 60% of Ba and 30% of Sr were implanted (see Verchovsky et al. 2004) with the rest being co-condensed with the SiC (Lodders & Fegley 1995). In similar fashion to Xe, the implanted Ba and Sr represent the low energy component associated with the main stage of AGB evolution. However systematic variations in the isotopic compositions of both Sr and Ba with grain size suggest that *s*-process Sr and Ba generated at a higher level of neutron exposure have a slightly different implantation energy compared to the same elements formed with lower exposure. Whether these components are associated with the same, or different, AGB stars remains uncertain.

Elemental fractionation in the low energy component between noble gases and alkaline-earth elements follows in general the dependence on ionisation potential. However, in detail there are some differences which require a more complicated scenario. In order to produce the observed Ba/Xe and Sr/Kr fractionation, the ionisation temperature should be ~10000K at thermodynamic equilibrium. However, the elemental fractionation between alkaline-earth elements requires a much lower temperature: ~5000K (Figure 2). This apparent discrepancy can be explained by proposing two wind components ionised at low (~5000K) and high (>13000K) temperatures with the latter being much less abundant than the former.

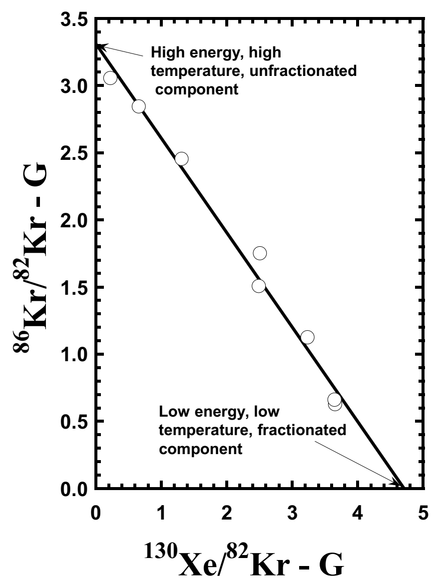

Fig. 1. Correlation of ^{86}Kr/^{82}K isotopic ratios with ^{130}Xe/^{82}K elemental ratios indicating a mixture of two components: 1) generated at low neutron density, fractionated during ionisation at low temperature, and implanted into SiC grains with low energies and 2) generated at high neutron density, completely ionised at high temperature and implanted into SiC grains with high energy. Data from Lewis et al. (1994).

2.2. The high energy component

This component also includes both *s*-process and isotopically normal noble gases. The former have extremely high implantation energies (~40 keV nucleon^{-1}) which is only compatible with post-AGB high-speed winds (n×1000 km s^{-1}) operating for a short period of time when the envelope becomes completely separated and the star reaches very high temperatures (up to 10^6K). This is the planetary nebula formation stage. Because of the high ionisation temperature, no fractionation is observed for the component (Figure 1). Isotopically this component consists of pure He shell material generated during the very late stage of AGB evolution. Therefore it is enriched with isotopes (such as ^{86}Kr, see Figure 1) formed at high neutron density. The isotopically normal noble gases have implantation energies a bit lower than that for the *s*-process component. It appears that these gases represent a portion of the envelope material which gained its energy when the high-speed (planetary nebula) wind overtook the low-speed envelope. This appears to have created enough relative speed between the envelope gases and SiC grains in order that the former could be implanted into the latter due to large differences in masses of the gas and grains.

3. Comparison with AGB wind theories

The scenario described above seems entirely plausible since it is quite compatible with the existing AGB wind theories (e. g. Lamers & Cassinelli 1999). In detail, however, there are a number of questions that still need to be answered. The most important of them is where the ions in the low energy components acquired their energy? In order to accelerate ionised atoms a magnetic field needs to be involved. Theories and observations do not give unambiguous answers regarding the existence of magnetic fields associated with AGB stars, though it has been suggested that AGB stars might have a central dynamo-induced magnetic field (Blackman et al. 2001), or local ones near the star surface (Soker 2002). Our scenario would tend to support the latter. In such a way it would be possible to account for the two low energy wind components and also explain the relatively high ionisation temperatures (5000K and 13000K (see section 2.1) compared to typical values (3000K) if we suggest that ionisation has occurred deep under the stellar surface, with the ionised material being brought to the surface by acceleration in local magnetic fields.

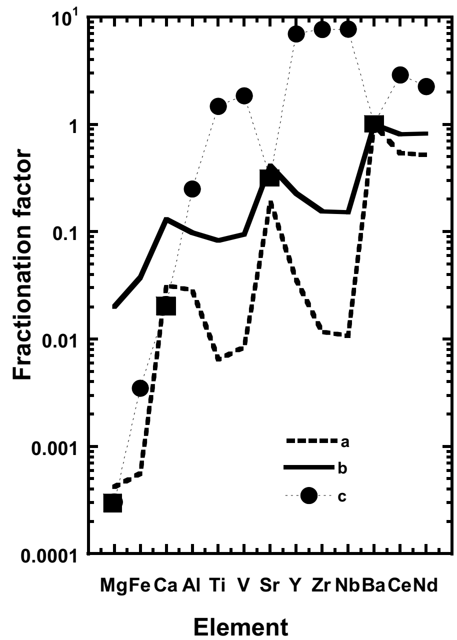

Fig. 2. Element fractionation during ionisation calculated for thermodynamic equilibrium at 4700 K (a), 9300K (b) and observed (average for all measurements) in the SiC grains and grain-size fraction (c) from the Murchison meteorite relative to CI composition (Amari et al. 1995)(b). In all cases normalization is made to the corresponding values for Ba. Alkaline-earth elements are highlighted with big squares.

The other important question is: why do neutral atoms not participate in implantation at all? The radiation pressure, dust-driven, AGB wind theory suggests that there is always some difference in the relative speed between gas and dust and this depends on the grain size of dust particles (formed in the AGB atmosphere) and rate of mass-loss. For instance, for the conditions existing for typical AGB stars (mass-loss rate $\sim 10^{-5}$ $M_\odot$ yr^{-1} and dust grain size 0.03-0.2 μm) the difference in the relative velocity of gas and dust could be as high as 10-200 km s^{-1} (MacGregor & Stencel 1992; Habing et al. 1994); this is enough for the gas atoms to be implanted into the dust particles. The only way to avoid implantation of neutral atoms is to propose that SiC grains found in meteorites have been formed in association with low mass-loss rate ($\sim 10^{-8}$ $M_\odot$ yr^{-1}) AGB stars that have envelopes containing relatively large (>0.5 μm) grains. Whether this is true or not remains to be seen.

On the other hand, one might suggest that elemental fractionation is not associated with ionisation but could be produced by other processes. For instance, radiation pressure mechanisms suggest that atoms accelerated by collisions with hydrogen would have energies that depended on their mass. However, the fact that there is a strong fractionation between Xe and Ba, which have nearly the same atomic masses, rules out this possibility.

4. Conclusion

The proposed implantation scenario for the origin of noble gases and alkaline-earth elements in meteoritic SiC grains is in general agreement with AGB star evolution theories, though some aspects of the scenario, such as the mechanism of acceleration of ionised matter in the AGB outflow and the absence of implanted neutral atoms in SiC grains, remain uncertain.

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