Isotopic Abundances in Presolar SiC Grains accounted by s-Processing from MHD-induced Mixing in low mass AGB stars

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October 2019

Abstract. In the past, the observational evidence that s-process elements from Sr to Pb are produced by stars ascending the so-called Asymptotic Giant Branch (or AGB) could not be explained by self-consistent models, forcing researchers to extensive parameterisations. The crucial point is to understand how protons can be injected from the envelope into the He-rich layers, yielding to the formation of $^{13}$C and then the activation of the $^{13}$C($\alpha$,n)$^{16}$O reaction. In the last decade, some physically-based mixing mechanisms have been considered to solve this problem. Nowadays, a big step forward in s-process studies would be to understand what is among the suggested ones the physical model better accounts for the observational constrains. In this paper we analyse a model where the $^{13}$C forms as a feedback of MHD processes in the stellar plasma. We compare results of nucleosynthesis models for low mass AGB stars (M<3M$_\odot$), developed from the MHD scenario, with the record of isotopic abundance ratios of s-elements in presolar SiC grains, which were shown to offer precise constraints on the $^{13}$C reservoir. We find that n-captures driven by magnetically-induced mixing can well account for the SiC data and that this is due to the fact that our $^{13}$C distribution fulfills the above constraints rather accurately. We show comparisons between model predictions and measurements for isotopes of Sr, Zr, Ba, Mo and Ru as representative examples of light and heavy s-elements.

1. Introduction

Cosmochemistry can provide a non electromagnetic probe to study stellar nucleosynthesis, indeed analysis of stellar dusts can provide precious pieces of information on the nucleosynthesis of the stars where dust grains form. Even if a dusty envelope hampers stellar observation, dust particles analysed in laboratory reveal the isotopic composition of their progenitor star with the precision of few per mils. This is the case for instance of the AGB stars, which are progenitors of the largest part of SiC grains found, as inclusions, in
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pristine meteorites. The composition of SiC presolar grains, and in particular the isotopic mix of MainStream grains (MS), has been for years a challenge to be explain [1].

In this paper, we show the comparisons of MS SiC grain composition with the output of a s-process nucleosynthesis model in which the $^{13}$C pocket formation has been triggered by the stellar magnetic field. We aim to verify whether our magnetic model can account for the isotopic mix of elements heavier than Fe recorded in grains of AGB origins. It is out of doubt that AGB stars are the dominate site main s-process component (namely the elements beyond Sr and Y, and lighter than Pb) in the Galaxy and that in objects with $M \leq 3 M_\odot$ the $^{13}$C($\alpha$,n)$^{16}$O reaction is the main source of neutrons, but it is instead matter of debate if magnetic fields in AGB stars are intense enough to develop the formation and the buoyance of instabilities able to promote a mixing, as firstly suggested by [2]. However, according to [3] and [4] the magnetic field of a few $10^5$ Gauss at the base of the stellar envelope would be sufficient to promote a mixing in the radiative region below. This value is similar to what found in the Sun and what hinted by maser effects observed in the spectra of a few single AGB stats [5].

Nowadays, more than 3000 MS SiC grains are recorded in the WUSTL presolar grains database and in the 10% of them heavy element abundances have been measured [6], these statistics are large enough that the sample average composition can be used as a benchmark for nucleosynthesis models. Moreover, several efforts have been done in the years by researchers to determine the size and the profile of the $^{13}$C reservoir that better accounts for the observations. Many models already provide a very nice fit to the isotopic abundance of s-elements recorded in presolar MainStream SiC grains (see e.g. [7, 8, 9, 10, 11]).

It is now time to address the problem by identifying the physical mechanism that shapes $^{13}$C pocket triggering its formation by an injection of protons from the stellar envelope into the He-rich layers at the moment of the third dredge-up (TDU). This task should be carried out without tuning the model parameters, or at least reducing at minimum this operation. Among the AGB models adopting a physically-based mixing mechanisms we mansion ones based on gravity waves [12] and on opacity-induced overshoot [13]. In this paper we discuss the result of our models, where the mixing is driven by the buoyancy of magnetised structure induced by a MHD (Magnetic Hydro Dynamic) process in the plasma [3]. Since this mixing has already been shown to account for the composition of oxide grains from O-rich AGB stars (if applied to the H-shell of AGB stars with $M \leq 2 M_\odot$ [14]) we now aim to verify wether it can also reproduce the composition of MainStream SiC grains (which form in the envelope of C-rich AGB stars). To do that the neutron flux delivered from the magnetic formed $^{13}$C pocket has to reproduce the signature of the s-process recorded in the isotopic composition of the grains.

2. Discussion and results

Being this work a test for the model, and not an effort to identify a stellar progenitor of the studied grains, we do not undertake any tuning of the parameters affecting the pocket shape, but we compare the abundances of a sample of grains (already proven to form in AGB stars by other authors [10, 6]) with the output of our s-nucleosynthesis code where the $^{13}$C reservoir
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![Graph showing comparisons](image)

**Figure 1.** Comparison between our model predictions and presolar-grain relative isotopic abundances for Sr, Zr and Ba. The plots report per mill values for the ratios $\frac{88\text{Sr}}{86\text{Sr}}$ (right panel) and $\frac{96\text{Zr}}{94\text{Zr}}$ (left panel) as a function of the ratio $\frac{135\text{Ba}}{136\text{Ba}}$. Data points are from [9, 10] and [6]. The curves show the evolution in time of the abundances in the stellar envelopes; the dots along the lines represent the various TPs. Model calculations are for AGB stars with mass from 1.5 to 3$M_\odot$ and metallicity from 1/3 solar to solar according to the following color code. Magenta: 1.5$M_\odot$ and $Z_\odot$/3; yellow: 2$M_\odot$ and $Z_\odot$; ciano: 2$M_\odot$ and $Z_\odot$/2; black: 2$M_\odot$ and $Z_\odot$/3; red: 3$M_\odot$ and $Z_\odot$; blue: 3$M_\odot$ and $Z_\odot$/2; green: 3$M_\odot$ and $Z_\odot$/3.

is shaped by the stellar MHD. The parameters of the model (namely the plasma diffusivity, kinematic viscosity, and the Prandtl magnetic number) are then determined by the physical conditions of the stellar layers below the convection at the moment of the third dredge-up (see [3] and [15] for details).

Since the correlation between light s-elements $ls$ and heavy ones $hs$ is a crucial constraint on the $^{13}$C pocket (see e.g. [9]), in figure 1 we compare the predictions of our model and grain data for both Zr (right panel) and Sr (left panel) isotopic ratios as a function of the $\frac{135\text{Ba}}{136\text{Ba}}$ ratio. These two plots are chosen as representative ones to show that isotopic abundances of elements belonging to both $ls$ and $hs$ group can be accounted for by the nucleosynthesis of AGB stars, whose $^{13}$C pockets form as a feedback of a mixing induced by the stellar magnetic fields. An extended discussion on this point can be found in the papers by [17] and [16]. In addition to the results shown in the quoted paper we report here the results achieved by our model in reproducing also the Mo and the Ru isotopic mix recorded in MainStream SiC grains ([6] and references therein). The comparisons between observed values and predictions, pulse after pulse, are reported in Figures 2 and 3, for Mo and Ru respectively. Even if in some cases, model curves do not completely overlap with the points, we believe that figures 2 and 3 present in any case a satisfactory agreement between models and measurements, in particular because error bars of grain data are sometimes relatively large.

This last achievement enforces our opinion that stellar magnetic fields can trigger the formation of the $^{13}$C pocket in low mass AGB stars and that the so-formed pocket can account for the s-element isotopic mix recorded in MainStream SiC grain. Moreover, the buoyancy of magnetised structures allows the formation of a pocket with a flat $^{13}$C distribution extended enough to account for the observational constrains coming from the chemical evolution of the
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Figure 2. Comparison between our model predictions and presolar grain abundances of Ru stable isotopes. The nucleosynthesis models and the notation used and the source of grain data are the same as in Fig 1.

Galaxy and the observations of open clusters [18]. All these findings make the magnetic model one of the most promising mechanisms to shape the formation of the $^{13}$C-pocket. Most likely, it is not the only one that needs to be taken into account. Indeed in the critical conditions at the border between the convective envelope and the radiative region in an AGB star, various instability phenomena must necessarily be present and any fast mechanism proceeding at m/sec velocities might contribute to inject protons in the He-intershell during the short time available at the TDU.

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Figure 3. Comparison between our model predictions and presolar grain abundances of Mo stable isotopes. The nucleosynthesis models and the notation used and the source of grain data are the same as in Fig 1.