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# Current hot questions on the *s* process in AGB stars

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**Abstract.**
Asymptotic giant branch (AGB) stars are a main site of production of nuclei heavier than iron via the *s* process. In massive (>4 $M_\odot$) AGB stars the operation of the $^{22}$Ne neutron source appears to be confirmed by observations of high Rb enhancements, while the lack of Tc in these stars rules out $^{13}$C as a main source of neutrons. The problem is that the Rb enhancements are not accompanied by Zr enhancements, as expected by *s*-process models. This discrepancy may be solved via a better understanding of the complex atmospheres of AGB stars. Second-generation stars in globular clusters (GCs), on the other hand, do not show enhancements in any *s*-process elements, not even Rb. If massive AGB stars are responsible for the composition of these GC stars, they may have evolved differently in GCs than in the field. In AGB stars of lower masses, $^{13}$C is the main source of neutrons and we can potentially constrain the effects of rotation and proton-ingestion episodes using the observed composition of post-AGB stars and of stardust SiC grains. Furthermore, independent asteroseismology observations of the rotational velocities of the cores of red giants and of white dwarves will play a fundamental role in helping us to better constrain the effect of rotation. Observations of carbon-enhanced metal-poor stars enriched in both Ba and Eu may require a neutron flux in-between the *s* and the *r* process, while the puzzling increase of Ba as function of the age in open clusters, not accompanied by increase in any other element heavier than iron, require further observational efforts. Finally, stardust SiC provides us high-precision constraints to test nuclear inputs such as neutron-capture cross sections of stable and unstable isotopes and the impact of excited nuclear states in stellar environments.

## 1. Introduction

Since the 1950s the products of *slow* neutron captures (the *s* process) have been observed at the surface of asymptotic giant branch (AGB). These include the presence of the radioactive element Tc, which represented the first evidence that nuclear reactions produce heavy elements in stars [1, 2]. Observationally, AGB stars are red giants characterised by strong stellar winds, which drive most of the stellar envelope into the surroundings. Theoretically, they represent the final phase of the lives of stars with initial mass between roughly 1 and 10 $M_\odot$, before their degenerate C-O, or Ne-O, cores are left as cooling white dwarves. During the AGB phase, *thermal pulses* (TP) occur in the He-rich *intershell* region located in-between the H- and the He-burning shells. During a TP, He burning releases a large amount of energy ($\sim 10^7$ $L_\odot$), which drives a convective zone in the whole intershell. The outer layers of the star expand and H burning shuts off. Eventually this convective zone extinguishes, He burning also shuts off, and the convective envelope may sink in mass, penetrate into the intershell, and carry the products of partial He burning to the stellar surface (the *third dredge-up*, TDU). These products include C, F, and the elements heavier than Fe produced by the *s* process. In AGB stars of initial mass greater than $\sim 4$ $M_\odot$, the base of the convective envelope can become hot enough to trigger proton-capture reactions, whose products are carried to the stellar surface directly by the envelope convection (*hot bottom burning*). See [3] for a detailed review on AGB stars.

The sources of free neutrons for the *s* process in the He-rich intershell of AGB stars are the $^{13}C(\alpha,n)^{16}O$ and the $^{22}Ne(\alpha,n)^{25}Mg$ reactions. The $^{22}Ne(\alpha,n)^{25}Mg$ reaction is activated inside the convective TPs when the temperature reaches above 300 MK, as it is happens in AGB stars of initial mass $> 3$ $M_\odot$ [4, 5, 6, 7, 8, 9]. In these conditions there is a significant impact of the still uncertain rate of the neutron source reaction on the final *s*-process abundances [8].

The $^{13}C(\alpha,n)^{16}O$ reaction is activated at lower temperatures, from ∼90 MK. While required by the observations that show that low-mass AGB stars are *s*-process enhanced, the formation of this neutron source is still a matter of debate. It is usually accounted for in the models by means of more or less artificial mixing of protons from the envelope into the intershell. These protons react with the abundant $^{12}C$ to produce $^{13}C$. In the most common scenario partial mixing of protons is included at the end of each TDU episode, under the assumption that the sharp discontinuity at the border between the convective envelope and the radiative intershell should favour the occurrence of such mixing. In practice, this mixing has been modelled via direct inclusion of $^{13}C$ [10, 11, 12, 13], direct inclusion of the protons leading to the formation of $^{13}C$ [14, 15, 7], or inclusion of an exponential decreasing profile of the diffusion coefficient [16] or of the convective velocity [17]. In all cases, free parameters allow us to adjust the extent in mass of the region affected by the mixing in order to match the observations. Usually, this extent represents a small fraction of the intershell ($1/10^{th}$-$1/20^{th}$) and the resulting thin $^{13}C$-rich layer is refereed to as the $^{13}C$ *pocket*. The bottom line is that we still do not know the actual mechanism by which the $^{13}C$ pocket forms. It could be overshoot of convective border beyond the standard Schwarzschild criterion [16, 17], gravity waves [18], semiconvection [19], rotational mixing [20], or other processes not yet investigated. In any case, all the mechanisms proposed so far give us a pretty much exponentially decreasing proton profile, which is why this is the choice made in the parametric models of, e.g., [7]. Clearly, a fully self-consistent 3D hydro-dynamical model of the formation of the $^{13}C$ pocket is needed but not available yet.

In AGB stars of mass between $\sim 1.75$ $M_\odot$ and 3 $M_\odot$, once formed, the $^{13}C$ pocket burns releasing neutrons in radiative conditions, before the onset of the following TP [10, 11, 14, 12, 15, 17, 21, 13, 7]. In this conditions, the total number of free neutrons at any given metallicity is determined uniquely by the number of $^{13}C$ nuclei minus the number of the $^{14}N$ neutron poison, whose neutron-capture reaction $^{14}N(n,p)^{14}C$ is relatively efficient. In this situation the impact of the uncertainties related to the $^{13}C(\alpha,n)^{16}O$ reaction is minimal [22]. On the other hand, stellar rotation may have a large effect on the final *s*-process distribution: a possible difference in the angular velocity between the contracting core and the expanding envelope generate mixing in the $^{13}$C pocket. As a consequecnce, $^{14}$N produced in the top layers of the pocket (for initial proton numbers > 0.01) is mixed into the underlying $^{13}$C-rich region, lowering the number of free neutrons. In this situation the *s* process can be completely inhibited, or modulated to lower efficiencies [23, 24, 25]. (See also S. Cristallo et al., this conference.) For stellar masses < 1.75 M$_\odot$, some $^{13}$C can be left in the pocket to be ingested and burn in the following TP [17, 21, 7]. In this case, the efficiency of the *s*-process is lower than in the (non-rotating) radiative $^{13}$C-pocket scenario as the $^{14}$N abundance is higher because this nuclues is ingested in the TP from the pocket and from the H-burning ashes.

Another way to produce the $^{13}$C neutron source is via ingestion of a small number of protons directly inside the TP [26, 27, 7]. Also in this case, the efficiency of the *s*-process is lower than in the non-rotating radiative $^{13}$C-pocket scenario. Such *proton-ingestion episodes* are well known to occur in AGB stars of low mass ($\sim$ 1 M$_\odot$) and low metallicity (< 0.0001) [28, 29, 30, 31, 27, 32, 33, 7], as well as in post-AGB stars [34]. The details of PIE events and the mass and metallicity range for which they occur are very uncertain because, as in the case of the formation of the $^{13}$C pocket, they rely on our incomplete understanding of convective boundaries in stars. First hydro-dynamical 3D models find many more proton ingested than 1D models [35] and preliminary 2D and 3D models of 2 M$_\odot$ stars of solar metallicity show that there is a finite mixing of material [36, 37]. When $^{13}$C burns convectively inside the TPs, the uncertainties related to the $^{13}$C($\alpha$,n)$^{16}$O reaction have a more significant impact [22] as they determine the time scale at which $^{13}$C burns, as compared to the time scale against which $^{14}$N is destroyed via $\alpha$ captures.

Results for AGB stars of initial masses between 0.9 M$_\odot$ and 6 M$_\odot$ at metallicity 0.0001 [7] have shown that the the final *s*-process abundance distributions for different stellar masses depend on the interplay of the different regimes described above. In general, when rotation is not included, $^{13}$C burning in radiative conditions produces higher total number of neutrons than $^{13}$C burning in convective conditions, due to the effect of $^{14}$N described above, but lower neutron densities because the burning time scale is longer.

## 2. Key Questions

### *2.1. Is the operation of the $^{22}$Ne neutron source confirmed in massive (>4 M$_\odot$) AGB stars? Is the $^{13}$C source also at work in these stars? Can massive AGB stars be responsible for the composition of the second stellar generation in globular clusters (GCs)?*

Massive AGB stars at the end of the AGB phase show [Rb/Fe] ratios from $\sim$1 to $\sim$5 dex [38, 39]. This can be considered as the signature of the high neutron density produced by the $^{22}$Ne source because $^{87}$Rb, a magic nucleus with a low neutron-capture cross section, is produced via the branching points at $^{85}$Kr and $^{86}$Rb. While this qualitative argument is probably correct (it also predicts the observed increases of Rb with increasing the stellar mass and decreasing the metallicity [6]) it has been shown that only models with a delayed mass loss have enough TP to reach close to the data [8]. Another main issue is that in the same stars that show high Rb enhancements [Zr/Fe]$\sim$0 [40] while *s*-process models can at most produce [Rb/Zr] up to 0.5 dex [6, 8]. This main problem is currently under investigation by means of updated models of the complex atmospheres of AGB stars, where pulsation and dust formation may also play a role in defining the stellar spectra.

While the observed massive AGB Rb-rich stars, being enshrouded by dust, are believed to represent the end of the AGB phase, massive AGB stars observed at the start of the AGB phase show solar abundances of both Zr and Rb together with no sign of the presence of Tc [41]. This constraint can be matched only by models where the $^{13}$C pocket is not included. The lack of neutrons from the $^{13}$C source in massive AGB stars was predicted theoretically due to the effect of “hot dredge-up” [42, 43].

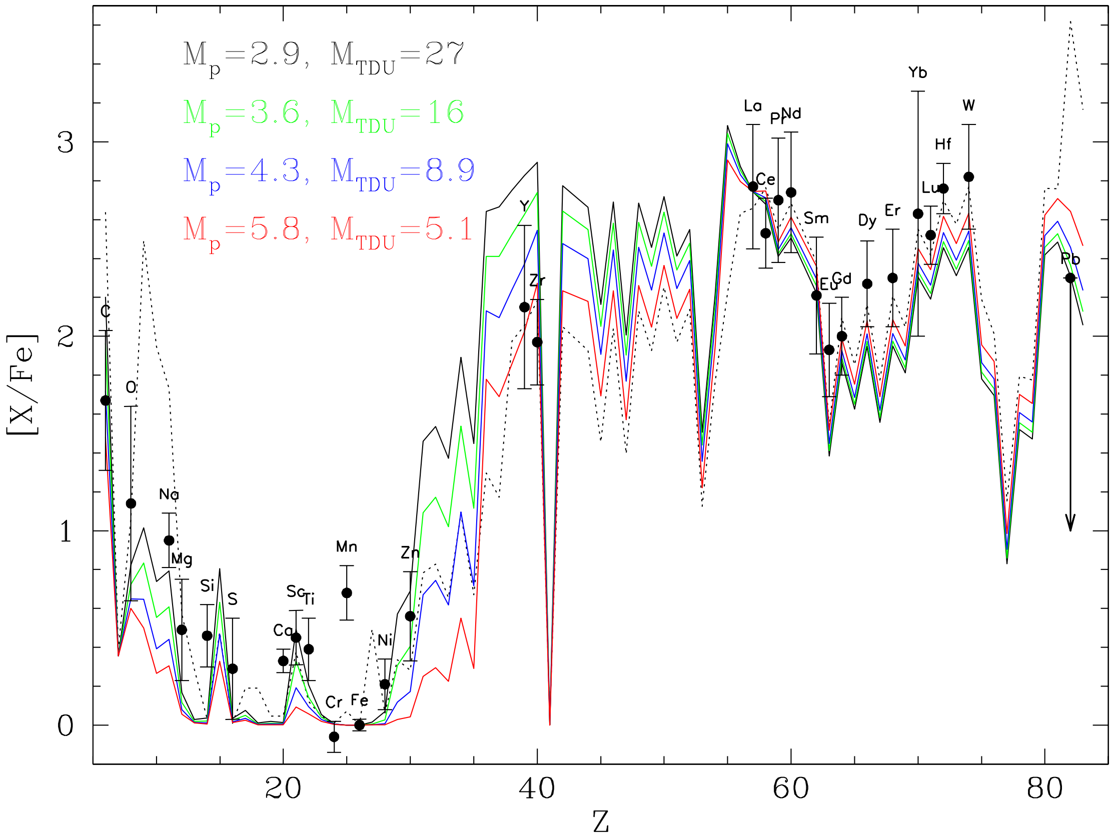


**Figure 1.** Comparison of AGB model predictions, computed on the basis of a stellar stucture with initial 1.3 $M_\odot$ and [Fe/H]=−1.3, to the composition of the post-AGB star J004441.04-732136.4 [46]. The dotted black line represents the results obtained introducing a $^{13}$C pocket resulting from the mixing an exponentially decreasing proton profile over a mass of 0.002 $M_\odot$ and with a parametric TDU of 0.0096 $M_\odot$. The TDU is fixed to match the observed [La/Fe] ratio. The colored lines represent the results obtained by artificially ingesting in the third-last TP a mass of protons between 2.9 and 5.8 (in units of $10^{-6}$ $M_\odot$), and with a parametric TDU between 5.1 and 27 (in units of $10^{-4}$ $M_\odot$).

Due to hot bottom burning, massive AGB stars represent one of the most popular candidate to explain the O, Na, Mg, and Al composition of the different populations in GC stars [44]. However, variations in these elements are not accompanied by any variations in *s*-process elements, not even Rb. This *s*-process constraint can be matched only if massive AGB models are evolved using a strong mass loss [9]. However, as discussed above, direct observations of Rb appear to require a weaker mass loss [8]. This may indicate that massive AGB stars evolved differently in GCs than in the field, perhaps due to different binary properties of the stellar population, affecting the stellar lifetime [45]. This needs to be investigated via stellar population synthesis models.

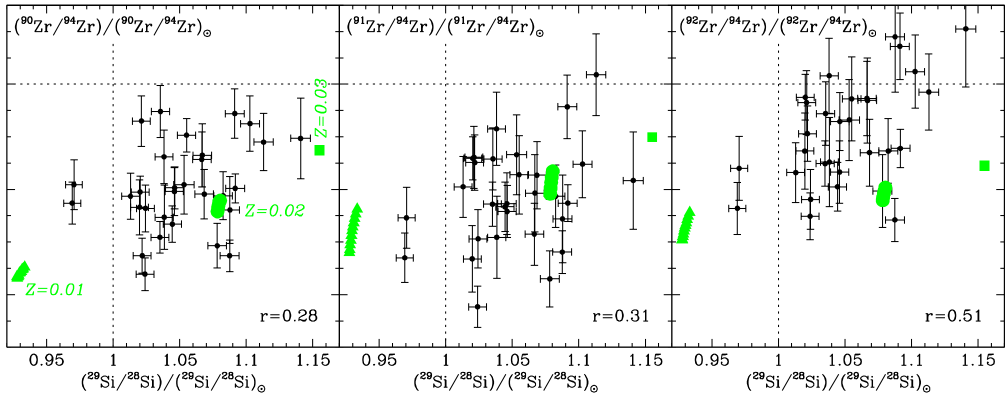


**Figure 2.** Comparison of Zr and Si data from SiC grains (black dots with 2$\sigma$error bars) with AGB models of 3 $M_\odot$ (green symbols for different metallicities Z, where solar = 0.014). The observed range of Zr ratios can be explained by changing the metallicity (as in the figure) or by the effect of rotation. If metallicity is the primary effect, we expect correlations between the Zr and the Si isotopic ratios, since the latter depend on the initial composition of the parent star. These correlations are hinted at in the small data sample currently available and it will be possible to confirm their existence (or lack of) via forth-coming studies. Also note that the SiC $^{92}$Zr/$^{94}$Zr ratios are on average significantly higher than the models, and new experiments at GELINA (Belgium) and n_TOF are aimed at re-evaluating the neutron-capture cross section of $^{92}$Zr. (Figure adapted from Lugaro et al. [48].)

*2.2. How does the* $^{13}$*C pocket operate in low-mass (<4* $M_\odot$*) AGB stars? Can we constrain the effects of rotation and proton-ingestion episodes?*

Recent observations of post-AGB stars in the Magellanic Clouds have provided us *s*-process abundances more reliable than those derived from observations of AGB star together with the opportunity to estimate the initial mass of the star to typical values $\sim 1\ \ 1.5$ $M_\odot$ [46, 47]. These post-AGB stars are characterised by *s*-process patterns that point to *s*-process efficiencies lower than those resulting by the non-rotating $^{13}$C-pocket models, as well as lower C abundances than predicted. As discussed above, both rotation and proton-ingestion episodes can produce lower *s*-process efficiencies than the non-rotating $^{13}$C pocket and we need to identify observational discriminants that can allow us to understand which of the two processes is responsible for the observed abundance patterns. We have started a parametric study to check for differences between the two scenarios. The first results of parametric models of proton-ingestion episodes are shown in Figure 1 and compared to J004441.04-732136.4. We confirm the results of de Smedt et al. [46] that the standard $^{13}$C-pocket scenario produces too much Pb and too much C to reproduce the observations. The proton-ingestion models can better reproduce the observed abundance pattern, including C, however, it is not possible to find an *s*-process efficiency (as determined by the number of protons ingested) that can reproduce the observed abundance of Zr, as well as of all the elements between La and W and at the same time does not, even if slightly, overproduce Pb above the given upper limit. This problem needs to be further investigated.

More constraints on the *s*-process in low-mass AGB stars come from the interpretation of the composition of the elements heavier than Fe in silicon carbide (SiC) grains recovered from primitive meteorites. The isotopic composition of these grains have been analysed to very high precision using resonance or secondary ion mass spectrometry (RIMS and SIMS, respectively) and show the clear signature of an origin in low-mass AGB stars, including strong signatures of the *s* process [49]. These measurements are extremely powerful especially when data are available for the same grain on a number of different elements. Lugaro et al. [48] suggested that an observed correlation (or lack of) between the Zr and Si isotopic ratios of SiC grains can be used to evaluate if rotation or metallicity variations are responsible for the range of Zr isotopic ratios measured in the grains (Figure 2). So far, only roughly 30 data points are available to study this effect, but more data will become available soon also thanks to the upcoming CHILI RIMS instrument [50].

Another way to independently constrain the effect of rotation is use asteroseismology observations. As described above, the efficiency of the *s* process in the $^{13}$C pocket depends on how fast the core rotates, which in turn depends on the initial velocity and the evolution of the angular momentum in the star. The latter can be modified by effects such as magnetic fields and gravity waves, which have not been considered in rotating *s*-process models so far. While it is difficult to infer rotational velocities for the cores of AGB stars from asteroseismology, it will be possible to derive them from models aimed at matching asteroseismic observations of the rotational velocities of the cores of red giants and of white dwarves, the stellar evolutionary phases just before and just after the AGB. Currently, the rotational velocities of white dwarves call for some braking effect due to, e.g., magnetic fields [51]. Furthermore, Mosser et al. [52] have observed a spin down of the core rotation in red giants, which requires a transfer of angular momentum in the star to spin down the core. Tayar & Pinsonneault [53] have shown that these observations can be explained only by complete coupling between the core and the envelope. The consequences of such studies on the *s* process needs to be investigated.

### *2.3. Is the standard s process enough to understand all the observations?*

Some of the most interesting objects in the halo of our Galaxy are the carbon-enhanced metal-poor (CEMP) stars. The majority of them is believed to have gained their C and *s*-process enhancement via mass transfer from a more massive binary companion while it was evolving through the AGB. About half of CEMP stars, the CEMP-$s/r$ stars, have enhancements in Ba, as well as in Eu, which cannot be explained by standard *s*-process models [13, 7]. Moreover, the Ba and Eu enhancements present a correlation ([Ba/Eu]$\sim$0.6, while the *s* process always produces [Ba/Eu]$\sim$0.9), which cannot be recovered by simply assuming high initial [Eu/Fe] ratio. As suggested by Lugaro et al. [7] the composition of these stars needs to be investigated in the light of a possible $s/r$ process with neutron fluxes in-between the *s* and the *r* processes, and possibly linked to proton-ingestion episodes.

Recent observations of elements heavier than Fe in open clusters also present us with a puzzle: they show Ba abundances increasing with decreasing the age of the cluster, however, all the other observed neutron-capture elements, e.g., Zr, La, and Eu are constant [54, 55, 56, 57, 58]. (See also T.V. Mishenina et al., this conference.) Is this an observational problem or we need another process that produces only Ba? Attempting an answer to this question requires first to confirm which trends are real. To this aim large homogeneous data samples are mandatory.

### *2.4. Given the important uncertainties in the stellar models can we still learn something on the nuclear physics of the s process?*

In spite of the large stellar model uncertainties, laboratory analysis of stardust SiC grains provide us with the isotopic ratios and the high precision needed to address nuclear physics issues. For example, the $^{92}$Zr/$^{94}$Zr ratios in SiC grains are on average still higher than models predictions [48] even when computed using the latest $^{92}$Zr(n,$\gamma$)$^{93}$Zr cross section measured at n_TOF [59]. Analysis of new experiments is underway to resolve this issue.

A new indirect estimate of the neutron-capture cross section of the unstable $^{85}$Kr, via $^{86}$Kr($\gamma$,n)$^{85}$Kr at TUNL has allowed AGB *s*-process models to predict the $^{86}$Kr/$^{82}$Kr ratio with the precision required to analyse this ratio in stardust SiC grains and derive that AGB models of low mass <1.5 M$_\odot$, where a large fraction of the $^{13}$C neutron source is ingested in the TPs, provide a possible match to the high ratios observed in SiC grains of large size (a few $\mu$m) [60].

Finally, new reliable data on Eu isotopic ratios in SiC, obtained after careful investigation of molecular interferences in SIMS [61] have pointed out the need of a revision of the $^{151}$Sm(n,$\gamma$)$^{152}$Sm reaction rate from the rate measured at n_TOF with very high precision [62], in line with the analysis of the effect of population of higher nuclear energy levels at stellar temperatures presented by Rauscher [63] (see T. Rauscher, this conference).

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