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Slow neutron captures as the signature of asymptotic giant branch stars

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Asymptotic giant branch (AGB) stars evolve from stars of masses roughly lower than ten solar masses and nuclear reactions in their interiors contribute to the cosmic abundances of many chemical elements, including C, N, and F. One of their main characteristic signatures is the production of roughly half of the abundances of the elements heavier than Fe via *slow* neutron captures (the *s* process). At the end of the last century, significant progress in stellar modelling, combined with the availability of nuclear physics inputs, allowed us to successfully predict and reproduce a variety of observational constraints, from the existence of Pb stars at low metallicity to the composition of stardust. However, in the past 10 years or so, not only we have not reached a firm conclusion on the formation of the main neutron source and on the origin of Sr, Y, and Zr; but, also, further uncertainties have appeared, related to stellar rotation and mixing as well as neutron-capture cross sections and β-decay rates. At the same time, we are confronted by a growing set of observational constraints that are not matched by the current models, from low Pb abundances in post-AGB stars to high Eu abundance in C-rich halo stars. We summarise the challenges we are facing, the current efforts to discover and exploit possible ways forwards, and some first successes.

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1. Introduction

At 4.6 Gyr old, our Sun is a *yellow dwarf* star, roughly a million Km in size. Energy against gravitational collapse is generated in its core via H burning. This stage of the life of our Sun will end in roughly 5 Gyr, when H is exhausted in the core. At this point, the energy production still occurs via H burning, but the region of burning will shift to a shell located just outside the core. The Sun will expand to roughly 200 times its current size, turn into a *red giant* star, and may engulf the Earth in the process. As the core lacks the energy required to substain itself against gravitational collaps, it will contract and heat up until it reaches a temperature high enough for He to start burning, and provide energy. However, He in the core will exhaust much quicker than H ($\sim$100 Myr) and, again, the energy generation will have to move to a shell located just outside the core, while the core itself contracts until electron degeneracy is able to substain it against gravitational collapse. The Sun will become a red giant for the second time, and enter the evolutionary phase known as the the *asymptotic giant branch* (AGB). On the AGB it will lose all the mass located outside the core, until the core is left as a *white dwarf*. The fate awaiting the Sun described above is common to all stars of initial mass up to roughly 8 $M_\odot$.

The structure of a star on the AGB can be simply described invoking two separate components: the very compact ($\sim 10^4$ km) degenerate core, made of the products of He burning (C and O), and the extended envelope, made mostly of H and He, and supported by the H- and He-burning shells located just above the core. The H- and He-burning shells, together with the He-rich layer located in-between them (the He *intershell*), comprise an extremely thin region of an AGB star, incorporating a mass $\sim 10^{-4}$ to 10^{-2} $M_\odot$. This region is very hot (up to hundreds MK) and dense (up to $\sim 10^4$ g/cm^3) so that, in spite of its thiness relatively to the whole star, it not only performs the fundamental function of generating the nuclear energy, but also it is a perfect environement for rich nucleosynthesis to occur. This is even more true because the H- and He-burning shells are activated alternately, resulting in peculiar nucleosynthetic signatures produced by the combination of both burning processes. The H shell is activated most of the time, while He burning occurs episodically, and every time it drives a convective region that extends within the whole He intershell (*thermal pulse*, TP). The outer layers expand and cool, so that H burning ceases and the convective envelope may sink in mass inside the He intershell and carry to the stellar surface the products of the H and He burning episodes (*third dredge-up*, TDU). These are, for example, carbon, fluorine, and the elements heavier than iron produced via *slow* neutron captures (the *s* process). The cycle of H burning, He burning, and potential TDU repeats tens to hundreds of times during the AGB lifetime. After several TDU episodes, an AGB star can even become *C-rich*, when the number of C nuclei, which initially is roughly half of that of O, overtakes the number of O nuclei (C>O).

While these nucleosynthetic and mixing processes occur in the deep layers, the outer layers of an AGB star also present peculiar phenomena: the star is constantly eroded by strong winds (up to 10^{-4} $M_\odot$/yr), which carry material into the stellar surroundings. The mass loss is driven by both strong pulsations and dust formation. Eventually the star becomes completely obscured in the optical wavelenghts and is instead visible as an infrared object, due to the glowing of the dust that surrounds it. From the evolution of the infrared spectrum it is also possible to derive information on the types and the sizes of the dust, and how the dust is processed while the star evolves along the AGB towards the end of its life.

We identify three different AGB "regimes", on the basis on the initial stellar mass:

1. "Low-mass" AGB stars comprise stars of initial mass roughly 1 to 4 $M_\odot$. They produce C (as mentioned above they can reach C>O at their surface via the TDU), fluorine, and roughly half of the cosmic abundances of the elements heavier than Fe via the *s* process. These stars are not hot enough to efficiently activate the ^{22}Ne(α,n)^{25}Mg neutron source reaction, which requires temperatures in excess of 300 MK, so ^{13}C(α,n)^{16}O is the main neutron source, which is activated already at 90 MK. The *s* process in low-mass AGB stars is the focus of this paper.

2. "Intermediate-mass" or "massive" AGB stars comprise stars of initial mass roughly from 4 to 8 $M_\odot$. A main difference from the previous case is that the inner edge of the convective envelope is hot (up to 10^8 K), H burning occurs there, and its products are carried to the stellar surface via convection ("hot bottom burning"). Due to this, massive AGB stars typically do not reach C>O, but produce large amounts of N instead, because C is burnt into N. They also may produce large excesses in Na, while F is destroyed. In these stars temperatures in the TPs can exceed 300 MK and the ^{22}Ne(α,n)^{25}Mg reaction is the main source of neutrons, while the ^{13}C neutron source is not expected to be efficiently activated. For more details about this AGB regime and the related *s* processing, we refer the reader to the paper by A. García-Hernandez, this conference.

3. "Super"-AGB stars comprise stars of initial mass roughly from 8 to 11 $M_\odot$. They are massive AGB stars "to the extreme" as they experience very hot temperatures, both at the base of the convective envleope and inside the TPs. The main difference with respect to the previous case is that, prior to reaching the AGB, they undergo C burning in the core, and so they have a O-Ne, rather than a C-O, core. For more details about Super-AGB stars we refer the reader to the paper by C. Doherty, this conference.

It should be kept in mind that while these different mass regimes are all collectively put under the AGB banner, they strongly differ from each other in that their lifetimes vary by two orders of magnitude. While low-mass AGB lifetimes are of the order of Gyr, the lives of massive and Super-AGB stars can be as short as a few tens of Myr. This has important implications when considering the impact of AGB nucleosynthesis on the chemical evolution of galaxies and stellar clusters. Massive and Super-AGB stars can pollute a stellar system very early in its life (living their signatures in, e.g., the early Milky Way and globular clusters), while the chemical contribution from the low-mass AGBs can only appear much later on, as the system evolves.

1.1 A short tale about the *s* process in low-mass AGB stars

Our understanding of how low-mass AGB stars fulfill their role as main producers of *s*-process elements in the Universe has developed in unexpected ways in the past decades. At the end of the last century, a very successful model resulted from the joint efforts of the nuclear physics community, in producing an almost complete set of experimental neutron-capture cross sections for the *s* process, and the stellar modelling community, in producing the first models of the *s* process based on full stellar evolutionary, rather than parametric, calculations. It had been already

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recognised that a thin ^{13}C-rich layer (*pocket*) is required in low-mass AGB stars to produce enough neutrons to match the observed *s*-process enhancements, and that a plausible way to generate this pocket is assuming some partial mixing between the H-rich envelope and the He-rich intershell at the deepest extent of each TDU. The seminal paper by Straniero et al. [1] demonstrated for the first time that the ^{13}C in the pocket does not burn while it is engulfed in the next convective TP, as previously thought, but instead it burns already during the H burning phase, in radiative conditions. The model was fully developed and analysed [2, 3, 4] and successfully reproduced many observational constraints: from the Rb/Sr observed in AGB stars [5] and their overall *s*-process patterns [6], to high-precision measurements of the composition of meteoritic stardust that originated in low-mass C-rich AGB stars [7].

The model even predicted the existence of Pb-rich stars at low metallicity [2], which were subsequently discovered [8]. Pb production at low metallicity results from the fact that the amount of ^{13}C in the pocket does not depend on the stellar metallicity (i.e., it is a *primary* neutron source), because it is produced by interaction of protons with the ^{12}C made from the initial He in the star. As the metallicity decreases, the number of neutrons produced remains constant, while the number of neutron captured decreases because there are less nuclei to capture them. Overall, the total number of free neutrons increases with decreasing the metallicity, and heavier and heavier elements up to Pb and Bi are created [9]. Thanks to this property, when the model predictions were included in calculations of the chemical evolution of the Galaxy, the solar and galactic abundances of the elements from Ba to Pb could be successfully reproduced [10, 11].

In summary, at the end of the last century, a high level of understanding of the *s* process in AGB stars was achieved. From the start of this century, however, new problems have appeared on top of unsolved old issues: we are still left with many stellar uncertainties; we cannot match several observational constraints; and we even still miss important nuclear physics inputs. The aim of this paper is to describe some of these current problems and propose possible ways towards their solution.

2. We are still left with many stellar model uncertainties

A long-standing question related to the current model is how the ^{13}C pocket forms. Partial mixing of protons from the envelope with ^{12}C in the intershell must occur at the deepest extent of each TDU. Several physical mechanisms to achieve this mixing have been proposed, from hydro-dynamical overshoot [12, 13], to gravity waves [14], semiconvection [15], and rotational mixing [16]. All the mechanisms proposed so far give us a pretty much exponentially decreasing proton profile. A self-consistent 3D hydro-dynamical model of the formation of the ^{13}C pocket would help addressing this long-standing debate but is not available yet. Several methodologies have been used so far to implement a ^{13}C pocket inside *s*-process model calculations: (i) insert a ^{13}C pocket directly in the calculations, i.e., the abundance of ^{13}C is treated as a relatively free parameter [1, 2, 6, 18]; (ii) insert a proton profile in the intershell and apply the basic assumptions that it is continuous and decreases with the mass depth [3, 17, 19]; (iii) insert some form of *hydro-dynamical overshoot* at the convective border [12, 13]. In all cases free parameters are used to adjust the extent in mass of the ^{13}C pocket and match the observations.

A second major issue is to evaluate the effect of stellar rotation. It is well known that mixing inside the pocket can be driven by stellar rotation [20, 21, 22]. Initially a rotating star is a rigid body, however, when it starts climbing the giant branch the core contracts and rotates faster, while the envelope expands and rotates slower. This difference results in a steep jump in the angular velocity at the core-envelope interface, where the pocket is located. Such a discontinuity drives mixing inside the pocket carrying ^{14}N into the ^{13}C-rich region. Because the cross section of the ^{14}N(n,p)^{14}C reaction is relatively high ($\simeq$1.8 mbarn), ^{14}N effectively steals neutrons from ^{56}Fe, inhibiting the production of the heavy elements (see paper by S. Cristallo, this conference). If the mixing is efficient we may end up with very little or even no *s* process at all. In other words, the production of the elements heavier than Fe in AGB stars strongly depends on the evolution of the angular momentum inside the star. This is currently poorly understood because the core and the envelope may be linked by the presence of magnetic fields and/or gravity waves, in which case the envelope can effectively act as a brake and slow down the core. However, we do not yet have an accurate description of these processes.

One opportunity to settle the question of the effect of rotation on the *s* process in AGB stars is to exploit and complement on-going investigation of independent constraints from stellar seismology. Some of the current most significant advances in our investigation of stellar physics are happening thanks to stellar seismology information from recent space satellite missions such as Kepler. Designed as a planet finding mission, Kepler has also led to a revolution in our understanding of red giant stars: using detailed photometry it has made possible to accurately determine if a red giant star is experiencing shell H burning or core He burning [23] and to derive the rotational velocity of the core [24]. Cantiello et al. [25] found that it is not possible to match the observed core rotational periods of red giant stars using models of rotating stars even including magnetic fields. They concluded that extra angular momentum transport processes need to be investigated. It is not possible to derive the core rotational periods of AGB stars because their luminosity is dominated by strong pulsations. However, by interpolating between the observed core rotational velocity during the core He-burning phase of red giant stars and the observed rotational velocities of white dwarfs, Cantiello et al. [25] have also shown that the evolution on the AGB, which is in-between, appears to occur at nearly constant core angular momentum. These findings represent a promising way to shed light on the evolution of angular momentum inside stars and, in turn, rotationally induced mixing inside the ^{13}C pocket and the *s* process efficiency in rotating stars.

Another opportunity to improve our understanding of the formation of the ^{13}C pocket and the effect of rotation is represented by analysis of meteoritic stardust silicon carbide (SiC) grains that originated in C-rich AGB stars. The current dataset of high-precision measurements of the composition of elements heavier then Fe present in trace amounts in SiC grains comprises of the order of 100 grains. However, this number is expected to increase by a great extent thanks to the advent of the CHILI resonance ionization mass spectrometer at the University of Chicago (see paper by A. Davis, this conference). Isotopic ratios close to magic numbers can strongly depend on the total number of free neutrons in the ^{13}C pocket, which, in turn is a function of the shape of the proton profile leading to the formation of the ^{13}C pocket and stellar rotation. Liu et al [26, 27], for example, conclude that a "flat" rather than the standard "decreasing-with-depth" ^{13}C pocket profile may be required to explain some of the grain data, and Lugaro et al [28] investigated the possible effect of metallicity variations, which, as described above, are also responsible for changing the total number of free neutrons in the ^{13}C pocket. In the future, thanks to CHILI, we may be able to disentangle the different processes shaping the neutron flux in the ^{13}C pocket using as contraints analysis of several different elements in many single stardust grains.

Finally, another question is related to the existence and impact of proton-ingestion episodes. In AGB stars of initial low mass (~ 1 M$_\odot$) and low metallicity ([Fe/H]< -2), the ^{13}C neutron source can also be produced due to ingestion of protons directly inside the convective TPs during the AGB phase [19, 29], and even in the core He burning region during the red giant phase [30]. This may lead to neutron-capture processes with neutron densities in-between the *s* and the *r* processes, the *i* process, which have been invoked to explain the mysterious abundance patterns shown by carbon-enhanced metal-poor stars observed in the halo (see below). However, the study of this process is in its infancy: still present are both stellar uncertainties related to mixing processes, which need 3D models to be assessed, as well as many nuclear uncertainties, as the neutron-capture path moves away from the valley of β-stability (see paper by M. Bertolli, this conference).

3. We cannot match several observational constraints

There are four direct observational constraints of the *s* process in low-mass AGB stars that are currently unmatched by the standard model:

1. The Eu/Ba ratio observed in many carbon-enhanced metal-poor (CEMP) stars, which were polluted by the nucleosynthetic products of a more massive binary companion during its AGB phase, is roughly twice the ratio produced by the *s* process. This mismatch has been tentatively attributed to a independent contribution by the *r* process (so that these stars are know as CEMP-*s*/*r*), however, this scenario does not explain the observed correlation between the Ba and Eu abundances, nor the high frequency of CEMP-*s*/*r* stars. Another possibility is that the observed abundance pattern is related to the *i* process [19, 31].

2. Travaglio et al. [32] investigated the galactic chemical evolution of the elements belonging to the first *s*-process peak, Sr, Y, and Zr and found that roughly 30% of their solar abundances were missing in the same model that well reproduces the Ba and the Pb abundances. They proposed the existence of a light element primary process (LEPP) in massive stars to solve both this discrepancy and the high Sr/Ba ratios observed in halo stars (see paper by M. Aoki, this conference). As the quest for such process continues (see paper by C. Fröhlich, this conference), also a debate has started on the question if the problem of the missing 30% from the solar abundances of Sr, Y, and Zr can be solved within the current *s*-process model uncertainties. For more discussion the reader is referred to papers by O. Trippella, S. Bisterzo, and C. Abia, this conference).

3. Observations of elements heavier than Fe in open clusters have shown an enhancement of Ba in young cluster [33]. While this has been confirmed by several other studies, it is still debated if the other *s*-process elements show the same excess [34, 35, 36, 37]. It is not possible for the standard *s* process to produce Ba and not other *s*-process elements, such as La and the *i* process has again been proposed as a potential way to interpret the data [38].

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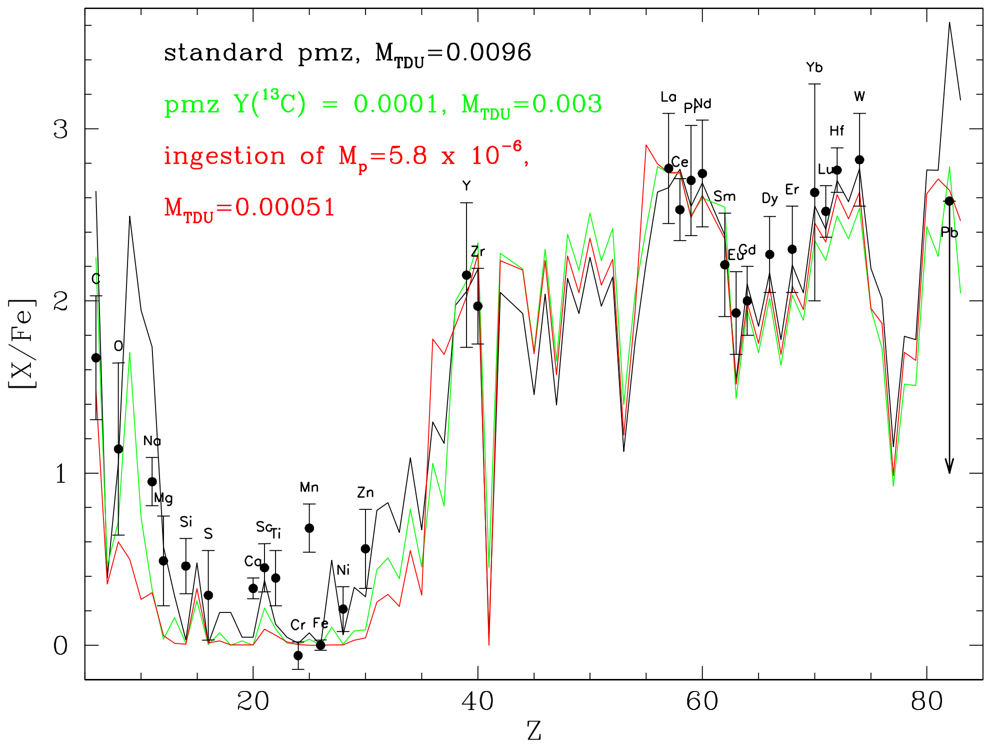

Figure 1: The abundance pattern observed in J004441.04-732136.4 as compared to three different low-mass AGB *s*-process scenarios: a standard ^{13}C pocket (black), a pocket with ^{13}C abundance of at most 0.0001 (green), and ingestion of a small amount of protons in a selected TP (red line). For each case we also indicate the amount of parametrised TDU mass required to match the observed [La/Fe] ratio.

4. Finally, we cannot match the low Pb abundances observed in post-AGB stars in the Magellanic Clouds. This problem is addressed in more length below.

Post-AGB stars are the evolutionary progeny of AGB stars. At this point of the evolution the star has lost most of its envelope, is left with a very thin H-rich layer ($\sim 10^{-3}$ M$_\odot$), and is evolving at constant luminosity towards higher temperatures. While abundance determinations for AGB stars are tricky, due to the complex nature of their pulsating, molecule- and dust-rich atmospheres, for post-AGB star spectroscopic abundance are relatively easier to derive. Recent observations of four post-AGB stars in the Magellanic Clouds, for which an initial stellar mass $\sim$ 1.3 M$_\odot$ was inferred comparing the absolute stellar luminosity to a theoretical evolutionary track, have presented a new challenge to the *s*-process models [39, 40, 41]. At the metallicity observed for these stars, [Fe/H]$\simeq -1.2$, the models predict a large abundance of Pb: the Pb/Ba ratio should be roughly 10 times higher than solar. The observations instead show that the Pb abundance is lower than that of Ba, relative to solar. Figure 1 illustrates the example case of J004441.04-732136.4 reported by [39, 41].

In Figure 1 we also show two possible scenarios to solve this Pb discrepancy. In one case, the neutron flux inside the ^{13}C pocket is strongly suppressed, with respect to the standard case. We simulate this by mixing protons with a flat abundance profile and a very low constant value of

0.0001, which effectively results in the production of the same number of ^{13}C nuclei. In the other case, the neutron flux is provided inside a selected TP rather than in a ^{13}C pocket, via parametrised ingestion of a small amount of protons. Clearly both scenarios can be fine-tuned to reproduce the observed abundances, however, it remain to be seen which of them can be explained as a true physical effect (rotation, overshoot, etc?) at work in these stars. The abundances of the light element, including C, O, F, and Na may help to discriminate between the different possibilities.

4. We even miss important nuclear physics inputs

Traditionally, nuclear physics input have been much more challenging to collect for the *r* process (away from the valley of β stability) than for the *s* process. Nevertheless, essential nuclear data for *s*-process modelling is still missing, inaccurate, or of low precision, which prevent us from obtaining reliable model predictions. Improved estimates of the ^{22}Ne(α,n)^{25}Mg and ^{13}C(α,n)^{16}O neutron source reactions are required and experiments have been on-going and planned (see papers by M. La Cognata and W. P. Liu, this conference). Furthermore:

1. A number of neutron-capture cross sections on the *s*-process path are not known to the precision required for model comparison, for example, to the high-precision stardust SiC data [28, 27]. Also, neutron-capture cross sections of unstable nuclei acting as branching points are often only known theoretically, with large uncertainties. Experimental facilities such as n_TOF at CERN, FRANZ in Frankfurt, and LiLit at SARAF will drive major progress in this context (see papers by C. Guerrero, C. Massimi, M. Paul, and I. Dillman, this conference).

2. For some specific nuclei the effect of the thermal population of excited levels in stellar conditions is significant but cannot be determined experimentally. This effect drives large uncertainties in the final evaluation of the cross section, which need to be analysed and tested individually for each nucleus (see paper by T. Rauscher, this conference).

3. Finally, the temperature and density dependence of β-decay rates of fundamental branching point nuclei are not well known.

A striking example is the β-decay rate of the ^{181}Hf branching point, which was predicted to have a strong temperature dependence due to the presence of a state at 68 keV [42]. This resulted in the terrestrial half life of 42 days to decrease to roughly 3 hours at *s*-process temperatures. However, Lugaro et al. [43] revised this dependence and found that the existence of the 68 keV state has not confirmed by more recent experiments. In fact, the β-decay rate of the ^{181}Hf branching point is long enough to allow for *s*-process production of the long-living ^{182}Hf (half life of 9 Myr). This solved a long-standing problem in the production of the ^{182}Hf abundance inferred in the early solar system via meteoritic analysis, allowing the dating of the last *s*-process event that contributed to build up the solar system *s*-process matter to 10-30 Myr before the formation of the Sun.

5. The message to take home

In summary, at the end of last century we had a successful model, but, from the start of this century problems have been piling up. The stellar asteroseismology revolution, stardust grains analysis (with CHILI), and detailed derivation of spectroscopic abundances in post-AGB stars are coming to the rescue by providing independent and high-quality observational constraints. A concerted effort of nuclear physicists and stellar modellers is required to improve and test neutron-capture cross sections and β-decay rates, whose determination is crucial to solving long-standing problems in the field.

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