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Models and observations of the *s* process in AGB stars

Maria Lugaro[*†]
University of Utrecht (The Netherlands) and Monash University (Australia)
E-mail: m.a.lugaro@uu.nl

Amanda I. Karakas[‡]
Mount Stromlo Observatory, Australian National University (Australia)
E-mail: akarakas@mso.anu.edu.au

Sara Bisterzo
Universitá di Torino (Italy)
E-mail: bisterzo@to.infn.it

Approximately half of the solar abundances of nuclei heavier than iron are created in the deep layers of asymptotic giant branch (AGB) stars via *slow* neutron captures (the *s* process). Freshly made heavy elements, such as Zr, Ba, and Pb, are carried to the stellar surface by recurrent mixing episodes and shed into the interstellar medium via strong stellar winds, thus contributing to the chemical evolution of galaxies. In the past few years several new modelling tools and observational constraints have added to our understanding of how the *s* process operates in AGB stars of different initial masses and metallicities. For AGB stars of low masses (≤ 4 M$_\odot$), the ^{13}C$(\alpha,n)^{16}$O reaction is the main neutron source. The exact mixing mechanism leading to the formation of ^{13}C is still unknown and multidimensional hydrodynamic models are needed to address this point. Recent stellar population modelling including *s*-process nucleosynthesis indicate that the spread in the efficiency of the ^{13}C neutron source is limited to a factor of two of the value obtained when reasonable basic assumptions are applied to the mixing mechanism. This is confirmed by new refined measurements of the isotopic composition of heavy elements in meteoritic silicon carbide grains. On the other hand, observations of the Rb and Zr abundances in massive AGB stars (> 4 M$_\odot$) indicate that the main neutron source in these stars is the ^{22}Ne$(\alpha,n)^{25}$Mg reaction. The increasing number of observations becoming available for the abundances of heavy elements in post-AGB stars and planetary nebulae, the progeny of AGB stars, can also be used to test the ideas above. At low metallicity, the main constraints for the *s* process come from observations of *s*-process-enriched carbon-enhanced metal-poor (CEMP) stars. In particular, the origin of CEMP stars enriched in both *slow* and *rapid* neutron-capture elements represent a challenge to our understanding of the origin of heavy elements.

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1. The *s* process

The *slow* neutron-capture process (the *s* process) is responsible for the production of about half the abundances of the elements heavier than Fe in the universe (see, e.g., [1]). The solar abundance distribution of the heavy nuclei made by the *s*-process is characterized by three peaks, corresponding to stable nuclei with magic numbers of neutrons N=51, the Sr, Y, and Zr peak, N=82, the Ba, La peak, and N=126, the Pb peak. This is because the *s* process is a flow of neutron captures along the valley of β stability, and nuclei with magic number of neutrons have small neutron-capture cross sections, with respect to other heavy nuclei. Hence, they act as bottlenecks along the *s*-process flux and produce the observed peaks. Typical neutron densities during the *s* process, i.e., for neutron captures to occur only along the valley of β stability, are of the order of $N_n \sim 10^7$ n/cm^3. For this value, any unstable nucleus produced by neutron captures has a timescale against capturing another nucleus that is much larger than the timescale of its β decay, which thus prevails all the time. In contrast, the *rapid* neutron capture process (the *r* process) occurs for $N_n > 10^{20}$ n/cm^3, in which case neutron captures always prevail against β decays.

In stellar conditions, neutron densities during the *s* process can reach values higher than 10^7 n/cm^3. In this case, depending on the peak neutron density, as well as on the temperature and density, which can affect β-decay rates, *branching points* open on the *s*-process path, allowing the production of neutron-rich isotopes otherwise destroyed during the *s* process. An important example of the consequences of the activation of branching points is the strong production of the element Rb, with respect to the neighbouring *s*-process elements Sr and Zr [2, 3]. This is achieved through production of ^{87}Rb via neutron captures on the unstable nuclei ^{85}Kr (for $N_n > 5 \times 10^8$ n/cm^3), and ^{86}Rb (for $N_n > 5 \times 10^9$ n/cm^3). Thus, the Rb/Sr, or Rb/Zr, ratios observed in stars can be used as an indicator of the neutron density during the *s* process, as will be described in Sec. 4.1.

1.1 Asymptotic giant branch stars

Asymptotic giant branch (AGB) stars are cool, red giant stars spectroscopically identified as members of the M, MS, S, SC, and C(N) classes. Since the 1950s, stars of this type have been observed to be chemically peculiar, in particular showing enhancements in *s*-process elements, such as Ba and Zr, as well as the presence of Tc, a radioactive element that can be produced by the *s* process. The presence of Tc in these stars was at first puzzling and later recognised as the first observational proof that nucleosynthesis does occur in stars. This is because Tc decays within a few million years, thus, it must have been produced *in situ* in the star where it is observed. The strong stellar winds observed in AGB stars, up to 10^{-5} M$_\odot$/yr, ensure that these stars are important contributors to the chemical evolution of galaxies and of the universe.

Theoretically, the last nuclear burning phase for stars of initial masses lower than approximately 8 M$_\odot$ is the AGB (see [4], for a review). During the AGB phase, the H- and He-burning shells are activated alternately on top of the degenerate C-O core (Fig. 1). Between the two shells is the so-called "intershell": a thin region (10^{-2} - 10^{-3} M$_\odot$) rich in He ($\simeq$ 75% by mass), and C ($\simeq$ 23% by mass) produced by partial He burning. The intershell increases in mass while the H-burning shell is active, until, after a few 10^3 to 10^4 yr, the He shell is compressed and heated

the time this work was prepared.

to the point when He burning is triggered (thermal pulse, TP). The sudden release of energy due to a TP drives convection in the whole intershell, while expanding and cooling the outer layers of the star. H burning is shut off during the thermal pulse and, after a few hundred years, also He burning is shut off. Before the H-burning shell is re-activated, and the so-called "interpulse" phase is re-established, the vast convective envelope sitting on top of the H shell can sink deep into the intershell mixing to the surface material that experienced He burning. This "dredge-up", of C in particular, is believed to be responsible for the increase of the carbon abundance observed in MS, S, SC, and C(N) stars, with C(N) stars occurring when the envelope becomes carbon-rich, i.e., C>O.

The dredge-up phenomenon - also referred to as “third dredge-up” (TDU), because it follows the first and the second dredge-ups during the previous red giant phases - is as fundamental for the chemical evolution of AGB stars, and for the galactic and stellar systems that they influence, as it is problematic to model. Its occurrence and efficiency depend on the physical and numerical treatment of convective borders in stellar interiors (see, for example, [5]). This treatment should account for phenomena such as turbulence, diffusion, rotation, and magnetic fields, which are very difficult to describe within one dimensional models. An answer on the amount of TDU in AGB stars may be provided by three dimensional models (such as those presented by Woodward et al., these proceedings). The other main uncertainty in modelling the evolution of AGB stars is the mass-loss rate, which determines the composition of the AGB envelope and the contribution of AGB stars to their environments. Much progress has recently been made in the modelling of the atmosphere of AGB stars (see [6] and reference therein). This will hopefully lead to an accurate description of mass loss in AGB stars, which is still missing, especially for low-metallicity objects.

The AGB lifetime is made of interpulse-TP-TDU cycles that can occur many times, terminating when the mass loss has removed the whole convective envelope. At this point the star moves onto the post-AGB track, a planetary nebula can form, if the material around the star is illuminated by the central hot star, and finally the degenerate core is left as a cooling white dwarf.

To complete the picture, AGB stars can experience proton-capture nucleosynthesis at the base of the convective envelope. This is found to occur in models of AGB stars of masses higher than about 5 $M_\odot$ (but decreasing at lower metallicities, see Fig. 2) and is known as hot bottom burning (HBB). The main result of this process is conversion of dredged-up C into N, and the possible production of Li. In AGB stars of lower masses, extra-mixing processes leading to proton-capture nucleosynthesis may also occur below the formal inner border of the envelope (see, e.g., Busso et al., these proceedings).

2. Models of the *s* process in AGB stars

A schematic representation of the current model for the *s*-process in AGB stars is shown in Fig. 1. Neutrons are released in the He-rich intershell in two different phases: during the interpulse period, when the ^{13}C$(\alpha,n)^{16}$O reaction is activated in radiative conditions, and during TPs, when the ^{22}Ne$(\alpha,n)^{25}$Mg reaction is activated in the convective regions. The ^{22}Ne$(\alpha,n)^{25}$Mg reaction needs temperatures higher than 300 million degrees to be efficiently activated, and these are reached only in the TPs of massive AGB stars. On the other hand, the MS, S, SC, and C(N) stars observed to be enriched in *s*-process elements are AGB stars of low masses, because of their luminosities [7], their radial velocities [8], and the fact that they have large C enhancements, thus

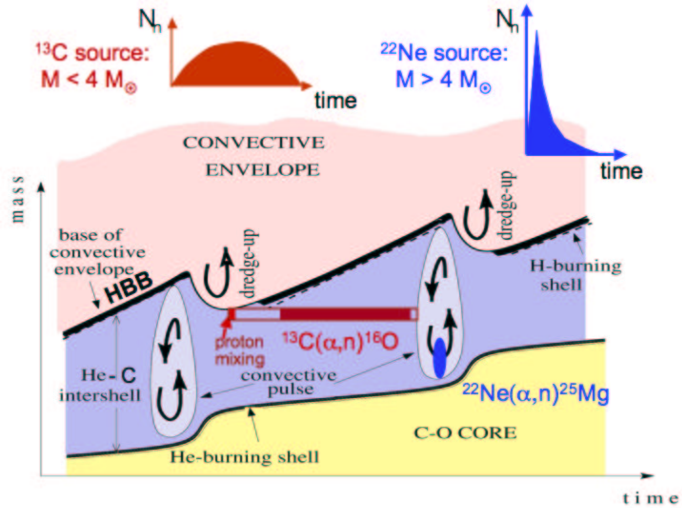

Figure 1: Schematic representation of evolution of the inner layers of AGB stars, also showing the locations where neutrons are released and (at the top) cartoons of the neutron density profile as function of time for the two neutron sources.

excluding the operation of HBB, which occurs in massive AGB stars. Thus, for the vast majority of *s*-enhanced AGB stars, ^{13}C has to be invoked as the main neutron source, given that the ^{13}C$(\alpha,n)^{16}$O is activated at lower temperatures, from approximately 90 million degrees.

The problem is that, while there is plenty of ^{22}Ne produced in the TPs via double α-capture on the abundant ^{14}N ingested in the TPs from the H-burning ashes, there is not enough ^{13}C in the H-burning ashes to produce the neutron fluxes needed to match the heavy element abundances observed in MS, S, SC, and C(N) stars. Thus, it is assumed that some protons mix into the intershell from the envelope, when a sharp discontinuity between the two regions is left at the end of each TDU. The protons are then captured by the abundant ^{12}C producing a ^{13}C-^{14}N "pocket". The temperature in the pocket increases to 100 million degrees before of the onset of the next TP and all the ^{13}C nuclei are consumed by ^{13}C$(\alpha,n)^{16}$O reactions during the interpulse period, as first reported by [9].

While several mechanisms have been proposed as the origin of the mixing leading to the formation of the ^{13}C-^{14}N pocket (semiconvection, hydrodynamical overshoot, gravity waves, rotation, see, e.g., [4] for discussion), as in the case of the TDU, a clear answer on the properties of such mixing and the ensuing pocket will only be provided by future three-dimensional calculation. In any case, one can employ the basic assumptions that the proton profile entering the intershell should be continuous, and that the mixing involves only a small fraction ($\simeq$1/20) of the whole intershell, corresponding to roughly a few 10^{-4} $M_\odot$ in low-mass AGB stars and to roughly a few 10^{-5} $M_\odot$ in massive AGB stars.

The ^{13}C and the ^{22}Ne neutron sources produce neutron bursts with contrasting features. The ^{13}C neutron burst occurs on a long timescale, of the order of 10^4 yr, the total number of neutrons released is very large, with time-integrated neutron fluxes of the order of a tenth to a few mb^{-1}, while the neutron density keeps low, up to $N_n \simeq 10^8$ n/cm^3. This neutron source produces the bulk of the *s*-elements, even reaching up to the third *s*-process peak at Pb in low-metallicity AGB stars.

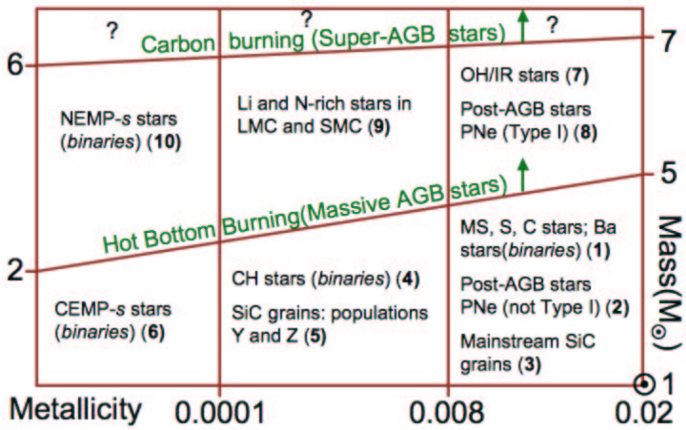

Figure 2: Types of observations of the *s* process in AGB stars of different masses and metallicities. References (corresponding to the numbers in bold): **1** [21, 2, 3]; **2** [22, 23]; **3** [24]; **4** [25]; **5** [26]; **6** [27]; **7** [28]; **8** [23]; **9** [29]; **10** [30], and references therein.

Branching points are mostly closed during this neutron flux. On the other hand, the ^{22}Ne neutron burst occurs on short timescale, of the order of a few years, the total number of neutrons released is small, with time-integrated neutron fluxes of the order of a few hundredth of a mb^{-1}, and the neutron density is high, reaching up to $N_n \simeq 10^{14}$ n/cm^3. This neutron source produces *s*-elements up to the first *s*-process peak at Sr. Branching points are mostly open during this neutron flux. The consequences of these different properties will be explored in Sec. 4.1.

s-process calculations based on the model described above and with inputs from stellar evolution calculations have been presented by [9] and [10], using stellar parameters computed by the Frascati Raphson Newton Evolutionary Code (FRANEC), and by [11], using the stellar parameters computed by the Brussels code. More recent and accurate models can be found in [12], who included the *s*-process network directly into the FRANEC code, and in [13, 14], who included an *s*-process network up to Nb in the Monash post-processing code, using stellar models of [15] computed using the MONSTAR evolutionary code [16].

A large set of yields for different stellar masses and metallicities was produced by R. Gallino and collaborators. These were included in the galactic chemical evolution models of [17, 18, 19], who analysed the evolution of the *s*-process elements in the Galaxy. A noticeable result of [19] is that AGB stars are unable to reproduce the whole solar *s*-process abundances of the elements up to Te, where some 20% to 30% of these abundances are missing from the models. A fraction of the abundances of these elements may instead be produced by charged-particle reactions (see Kratz et al., these proceedings). The *s*-process yields from [10] where also included in the stellar population synthesis model of [20]. Results from this new approach on the *s*-process in AGB stars will be outlined in Secs. 4.2 and 4.3.

3. Observations of the *s* process in AGB stars

The *s*-process model described above can be compared to many observational constraints. Some observations, such as the composition of MS, S, SC, and C(N) stars, can be directly compared to the models, others can be compared to the models only after further assumptions are employed. For example, to understand the composition of Ba, CH, and carbon-enhanced metal-poor (CEMP) stars, which presumably derived their *s*-process enhancements from a former AGB companion, modelling of the binary mass transfer scenario is required.

In Fig. 2 the mass-metallicity parameter space for AGB stars is represented and divided in different regions, depending on the different model features when varying such parameters. It is possible to find the corresponding observational constraints in each region of the parameter space, except for the highest-masses, where AGB stars turn into "super-AGB" stars and experience core carbon burning. For these stars no detailed nucleosynthetic models are yet available, even if recent efforts have been performed in the study of these stars, e.g., by [31].

4. Comparison of models and observations

4.1 The neutron source for different stellar masses

In Sec. 1 we noted that the Rb/Zr ratio observed in AGB stars is a discriminator of the neutron density. Given that the neutron density is higher by up to 6 orders of magnitudes in massive AGB stars, where ^{22}Ne is the main neutron source, with respect to low-mass AGB stars, where ^{13}C is the main neutron source (see Sec. 2), observations of the Rb/Zr ratio in massive OH/IR stars as compared to lower-mass AGB stars can be used to test theoretical predictions. This comparison reveals that, at least qualitatively, the model is correct: models of massive AGB stars and observations of OH/IR stars [28] show Rb/Zr ratios higher than solar. On the other hand, both models of low-mass AGB stars and observations of MS, S, SC, and C(N) stars [2, 3] show Rb/Zr ratios lower than solar. Quantitatively, it appears difficult to reach the Rb abundances up to two order of magnitude higher than solar observed in some OH/IR stars, however, uncertainties are large both observationally (almost one order of magnitude) and theoretically. Note that the Zr abundance is observed to be roughly solar in these stars. This is compatible with AGB models if they are computed without the inclusion of the ^{13}C neutron source. More details on this topic can be found in van Raai et al., these proceedings.

4.2 The ^{13}C-^{14}N pocket at solar metallicity

As discussed in Sec. 2, the features of the ^{13}C-^{14}N pocket are still a main uncertainty in the current *s*-process models. The local abundances of ^{13}C and of ^{14}N in the different layers of the pocket determine, at any given metallicity, the number of free neutrons available for the *s* process (the ^{13}C *efficiency* hereafter). Treating this efficiency as a free parameter [32] used a spread of a factor of 50 for this parameter to cover observed *s*-process distributions. In a similar fashion, [24] used a spread of 24 for the same parameter to cover data from single mainstream SiC grains.

Recent stellar population synthesis models including the *s* process, instead, derive a spread of $\simeq 2$ in the ^{13}C efficiency when compared to observations of MS, S, SC, C(N), Ba, and post-AGB stars [20]. In these simulations a large numbers of stars ($\sim 10^5$ stars) are evolved with a fine grid of masses, and to each model a probability is given, also accounting for evolutionary timescales. In this way, variations of the *s*-process distribution during the evolutionary time of AGB stars are modelled in detail and can account for the observed spread without having to invoke a large variation in the ^{13}C efficiency (see [20] for more details). This result is confirmed by improved measurements of heavy elements in mainstream SiC grains by [33] and [34] that also show that a spread of $\simeq 2$ in the ^{13}C efficiency is enough to cover the data.

4.3 The ^{13}C pocket at low metallicity: CEMP stars

Bisterzo [35] compared single star models based on the FRANEC code to abundances in 74 CEMP stars showing *s*-process enhancements (CEMP-*s*) and obtained best fits for each star by varying three parameters (see, e.g., [36]) : (1) the initial stellar mass, which gave best fits in the range $\sim$1.2 $M_{\odot}$ to 2 $M_{\odot}$ - for higher masses, efficient activation of the ^{22}Ne neutron source produces higher abundances of light *s*-process elements, as well as of Na and Mg, than observed; (2) the dilution factor due to mass transfer from the AGB companion, which resulted to be smaller for main sequence CEMP stars than for giant CEMP-*s* - perhaps indicating that thermohaline mixing does not have a strong effect on the abundances of CEMP stars; (3) and the ^{13}C efficiency, which was typically ~ 10 times lower than in the solar metallicity case.

4.4 The mystery of CEMP-$s+r$ stars

CEMP-$s+r$ stars show large *s*- (e.g., Ba/Fe) and *r*-process (Eu/Fe) enhancements of $\sim$ ten times solar, and represent a relatively large fraction, 30% to 50%, of the CEMP-*s* population. Several scenarios have been proposed to explain this peculiar chemical composition (see, e.g., [27]), the favourites of which can be classified into two main classes, both invoking a binary system. In the first class, the binary system was born out of material contaminated by a nearby supernova, providing the *r*-process elements, and then the primary star evolved into the AGB phase, providing the *s*-process elements via mass transfer to the secondary now observed. This scenario, however, can not account for the very large fraction of CEMP-$s+r$ among CEMP-*s* stars, unless formation of binary systems is favoured during triggered star formation [37]. It is also to be analysed in detail if this scenario can account for the observed correlation between the *r*- and the *s*-process enhancements (see Fig. 7 of [27]). In the second class, the primary star evolved into the AGB phase, providing the *s*-process elements, and then exploded as a supernova, providing the *r*-process elements. Making an AGB star explode, however, is extremely difficult: only AGB stars of relatively high masses (4 $M_{\odot}$ or more) may explode as electron-capture supernovae or supernovae of type 1.5 (i.e., if the core reaches the Chandrasekhar mass). However, because of HBB, companion masses in this range would produce nitrogen-enhanced metal-poor (NEMP) stars, rather than CEMP stars.

5. Summary, discussion, and future directions

- At least qualitatively we understand which are the dominant neutron sources in the different stellar AGB mass ranges: ^{13}C for the lower masses, ^{22}Ne for the higher masses.
- A small spread of ^{13}C efficiency is needed to match observations at any given metallicity. This is reasonable if a continuous proton profile is assumed (see discussion in [11]). If rotation is included in the AGB model, it drives mixing in the pocket, which would completely

inhibit the *s* process, or may induce a large spread in ^{13}C efficiency [38, 39]. However, models that also include magnetic fields indicate that strong rotational mixing may be in turn inhibited by the presence of such fields [40].

- At low metallicity, a smaller (∼1/10) ^{13}C efficiency is needed. This point requires further investigation, but is possibly related to the presence of the primary ^{14}N in the pocket, which is the most important light neutron poison. Note that the interplay between diffusive mixing and nuclear burning during the TDU does lead to a lower ^{13}C efficiency in low-metallicity AGB stars (see [41, 42]). However, this happens only for masses higher than 3 $M_{\odot}$.

- Three dimensional mixing models are needed to pin down the TDU efficiency and the formation of the ^{13}C-^{14}N pocket.

- Many of the observational constraints for the *s* process in AGB stars come from *s*-rich main sequence and red giant stars where binarity is a fundamental process to be considered. However, we still miss detailed simultaneous AGB evolution+binary models.

- We needed to work hard on possible scenarios for the mysterious CEMP-$s+r$ stars before we can feel confident of our understanding of the *s* process and AGB evolution at low metallicity.

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