PROCEEDINGS OF SCIENCE

The *s*-process in AGB stars

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About half of the solar abundances of elements heavier than iron are made by the *slow* neutron capture process (the *s* process) occurring in low and intermediate-mass asymptotic giant branch (AGB) stars. Elements are dredged from the core to the surface and then expelled into the interstellar medium through strong stellar winds. In comparison to the *rapid* neutron capture process, modelling the *s*-process has presented fewer difficulties because most of the nuclei involved are near the valley of stability and therefore available for experiments. Also, many giant stars are observed with enrichments of heavy elements produced by the *s* process, providing unique constraints on stellar nucleosynthesis models. However, many important uncertainties still remain including the mechanism leading to the formation of ^{13}C pockets where ^{13}C is the main neutron source, and the efficiency of convection leading to the third dredge-up in AGB stellar models. There is an increasing wealth of observational data that is being used to constrain *s*-process modelling in AGB stars. These include spectroscopic abundances from AGB stars and their progeny (post-AGB stars, planetary nebulae), pre-solar meteoritic grains, globular cluster stars, and very metal-poor halo stars with enrichments of carbon and *s*-process elements. The current status of AGB *s*-process models is reviewed, followed by recent efforts to use the heavy-element composition of planetary nebulae as constraints on mixing and nucleosynthesis in AGB stars. Finally, we discuss a new potential site of the *s*-process: the dual-core He-flash in primordial low-mass giant stars.

11th Symposium on Nuclei in the Cosmos, NIC XI
July 19-23, 2010
Heidelberg, Germany

*Speaker.

PoS(NIC XI)042

1. Introduction

The solar abundance distribution of elements heavier than iron is characterized by peaks that can be explained by the *slow* neutron capture process, the *s* process, and the *rapid* neutron capture process, the *r* process. There are also a small number of proton-rich nuclei that are much less abundant in the solar system than nuclei synthesized by the *s* and *r* processes. For an historical overview of the neutron-capture processes we refer to [1] and references therein. We will concern ourselves with the *s* process, which occurs under conditions of relatively low neutron densities ($N_{\rm n} \sim 10^7$ neutrons/cm^3). In this case the timescale for neutron capture is much slower, in general, than the β-decay rate of unstable isotopes. Hence, the *s* process produces isotopes along the valley of β-stability. In contrast, during the *r* process neutron densities as high as $N_{\rm n} \sim 10^{25}$ neutrons/cm^3 ensures that the timescale for neutron capture is much faster than the β-decay rates. For more details of the *r*-process we refer to reviews by [1] and [2].

The solar abundance distribution of the elements heavier than Fe show peaks that are constrained by nuclei with a magic number of neutrons ($N = 50, 82, 126$). In practice, nuclei with a magic number of neutrons are very stable against neutron capture and have low neutron capture cross sections. Hence these nuclei act as bottlenecks and are consequently seen as *s*-process peaks around Sr ($Z = 38$), Ba ($Z = 56$), and Pb ($Z = 82$). We can define the neutron exposure, τ as the time-integrated neutron flux with units of mbarn^{-1}. Historically, the *s* process has been separated into three components: 1) the weak component that produces most of the *s*-process elements from Fe to Sr (produced with a single exposure of $\tau \approx 0.07$ mbarn^{-1}); 2) the main component that requires a mean $\tau \approx 0.3$ mbarn^{-1} and produces isotopes from $90 \lesssim A \lesssim 204$; and 3) the strong component that operates under conditions of high neutron exposure ($\tau \approx 7.0$ mbarn^{-1}) and is responsible for most of the Pb production in the Galaxy [3]. The weak component occurs in the He and C-burning shells of massive stars [4], the main component in low-mass ($\sim 1 - 3M_\odot$) asymptotic giant branch (AGB) stars [5], and the strong component occurs in low metallicity, low-mass AGB stars [6]. For reviews on the operation of the *s* process in AGB stars we refer to [5], [7], [8].

2. The *s*-process in AGB stars

Briefly, during the thermally pulsing-AGB (TP-AGB) phase the He-burning shell becomes thermally unstable every 10^5 years or so, depending on the H-exhausted core mass (see Fig. 1 for the schematic structure of an AGB star). The energy from the thermal pulse drives a convective zone in the He-rich intershell (which lasts for $\approx 10^2$ years), that mixes the products of He-nucleosynthesis within this region. The energy provided by the thermal pulse expands the whole star, pushing the H-shell out to cooler regions where it is almost extinguished and subsequently allowing the convective envelope to move inwards (in mass) to regions previously mixed by the flash-driven convective zone. This inward movement of the convective envelope is known as the third dredge-up (TDU), and is responsible for enriching the surface in ^{12}C and other products of He-burning, as well as heavy elements produced by the *s* process. Following the TDU the star contracts and the H-shell is re-ignited, providing most of the surface luminosity for the next interpulse period. The cycle of interpulse–thermal pulse–dredge-up may occur many times on the AGB,

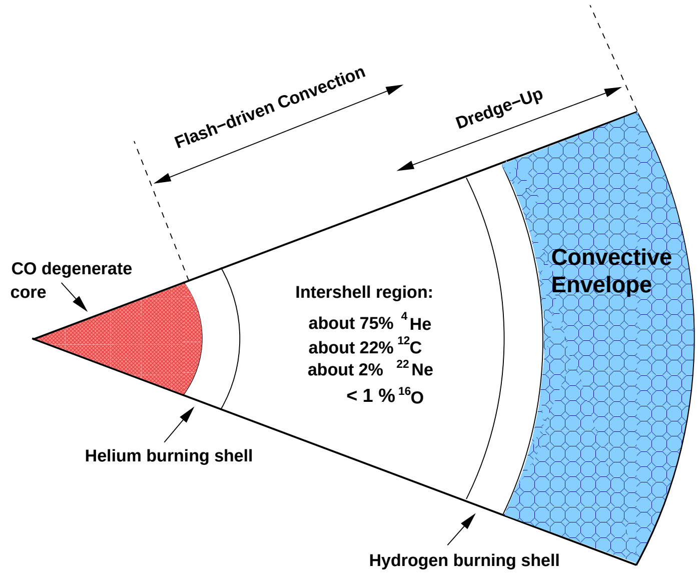

Figure 1: Schematic structure of an AGB star showing the degenerate C-O core surrounded by a He-burning shell above the core, and a H-burning shell below the deep convective envelope. The burning shells are separated by an intershell region rich in helium ($\sim$ 75% by mass) and carbon ($\sim$ 22%). It is the intershell region that becomes enriched in *s*-process elements. Note that the figure is not to scale. From [9].

depending on the initial mass and composition, as well as on the mass-loss rate. We refer to [10] for a overview of the evolution of AGB stars.

In intermediate-mass AGB stars ($M \gtrsim 4M_{\odot}$ depending on metallicity, Z) the convective envelope can penetrate into the top of the H-shell, resulting in nuclear burning at the base of the convective envelope [11]. This phenomena is known as hot bottom burning (HBB) and can dramatically alter the surface composition. This is because the convective turn-over time of the envelope is ≈ 1year, hence the whole envelope is processed through the hot region a few thousand times per interpulse period. Efficient TDU results in a significant production of primary ^{14}N via HBB (using the primary ^{12}C dredged from the He-shell). Intermediate-mass stars enter the AGB with core masses $\gtrsim 0.8 - 1.2M_{\odot}$ and will evolve more rapidly than their lower mass counterparts. For these stars the typical interpulse period is 10^{3} years and the duration of the convective zone in the intershell on the order of ≈ 10 years. In the Galaxy, intermediate-mass AGB stars are difficult to identify owing to a lack of reliable distances. This has resulted in a paucity of observational evidence for constraining stellar models. For example, while models predict efficient TDU in intermediate-mass AGB stars, this predictions has been difficult to verify from observations. Observations of bright O-rich AGB stars in Magellanic Clouds reveal that these stars can become C-rich and *s*-process rich, indicating efficient dredge-up at Magellanic Cloud metallicities [13, 14]. Clearly work is to be done determining the efficiency of mixing in the AGB stars with HBB. Note also that the efficiency of the mass-loss rate as well as other input physics, such as opacities, play a strong role in determining the final yields from intermediate-mass stars

The *s* process is driven by the production of free neutrons that are subsequently captured by Fe-peak seed nuclei to form heavier elements. The first neutron source suggested to operate in AGB stars was the ^{22}Ne$(\alpha,n)^{25}$Mg reaction [15]. Later, [16] suggested this reaction was the dominant source in intermediate-mass AGB stars, because the He-shells of these stars reach high enough temperatures ($T \gtrsim 300 \times 10^6$ K) to allow for this reaction to be efficiently activated (e.g., [17]). In contrast, these temperatures are reached only in the last few thermal pulses of a lower mass AGB star. [16] found that the ^{22}Ne source results in enhanced levels of Rb owing to the high neutron densities (up to $\sim 10^{13}$ neutrons/cm^3), as well as increases in ^{25}Mg and ^{26}Mg from the competing reactions ^{22}Ne$(\alpha,n)^{25}$Mg and ^{22}Ne$(\alpha,\gamma)^{26}$Mg [18, 19]. Fenner et al. [20] compared results from a chemical evolution model with observations of the neutron-rich Mg isotopes and concluded that an extra production site besides Type II supernovae was necessary, and that massive AGB stars with efficient TDU are a good candidate for such a site. There is, however, some uncertainty at what Galactic epoch AGB stars started contributing to the chemical enrichment of the Galaxy [21, 22]. It is still not known to what extent intermediate-mass stars contribute to the Galactic inventory of *s*-process elements.

The other potential source of neutrons in AGB stars is the ^{13}C$(\alpha,n)^{16}$O reaction, which operates at lower temperatures ($T \gtrsim 90 \times 10^6$) than the ^{22}Ne source. Observational and theoretical evidence suggests this is the dominant neutron source in low-mass AGB stars [23, 24]. To operate efficiently, this reaction requires more ^{13}C than is left over from CN cycling in the H-shell. For this reason some mechanism to mix protons from the H-rich envelope into the intershell is needed to produce the extra ^{13}C. The details of how the a ^{13}C-rich region ("a pocket") forms and its extent in mass in the He-intershell are still unknown although various mechanisms have been proposed, including convective overshoot, rotation, and gravity waves. In AGB models today there are two commonly used methods to achieve a ^{13}C pocket. The first uses some form of convective overshoot [25, 26], whereas the second method artificially adds a ^{13}C (or H, where the protons will quickly be captured by the abundant ^{12}C to form ^{13}C) profile of a specified size and shape into the He-intershell (e.g., [27, 17, 28]). In the second method any potential feedback of the formation of the ^{13}C pocket on the structure of the star is ignored. In intermediate-mass models the temperature at the base of the convective envelope during dredge-up may become hot enough for proton-capture nucleosynthesis [29, 30]. The energy produced by these "hot dredge-ups" may effect the structure of the star, by increasing the depth of dredge-up [30], or by terminating the AGB altogether [31]. This situation could arise if the ingestion of protons leads to an hydrogen flame that produces enough energy to eject the envelope [31]. Consequences of proton ingestion on the nucleosynthesis are largely unknown but could include the inhibition of formation of the ^{13}C pocket [29]. Further detailed studies into the effects of a partial mixing zone on AGB nucleosynthesis are required.

In the ^{13}C pocket neutrons are typically liberated by the reaction ^{13}C$(\alpha,n)^{16}$O during the interpulse period [32], in contrast to the ^{22}Ne source which operates during thermal pulses. The timescales for neutron production during the interpulse are much longer ($\gtrsim 10^3$ years) than during the convective pulse (~ 10 years), resulting in much lower neutron densities ($\sim 10^7$ neutrons/cm^3) than the ^{22}Ne source. However the time-integrated neutron exposures are much higher in the ^{13}C pocket than in thermal pulses. Together, the neutron exposure and the neutron density determine the resulting *s*-process element distribution.

3. Latest theoretical models

The details of AGB nucleosynthesis depends on a number of factors including the efficiency of the third dredge-up, the minimum H-exhausted core mass for the onset of the TDU, and the minimum mass for the onset of HBB. All of these quantities in turn depend on the stellar mass, metallicity, and/or envelope mass, and these change during evolution along the AGB. HBB for example, will be shut off once the envelope mass drops below some critical value as a result of strong mass loss. The mass-loss rate also determines the total number of thermal pulses and this then sets the level of enrichment in the envelope. All of these quantities depend on large uncertainties related to the stellar modelling. Most of these uncertainties stem from our inability to accurately model convection in stellar interiors, although other inputs such as the mass-loss rate and opacities also play an important role.

The study by Marigo [33] showed that inclusion of C-rich low-temperature opacities was an important addition to the modelling of TP-AGB stars. That is because the C dredged into the envelope forms C-bearing molecules (such as CO, CN) that lead to a strong increase in the opacity. The increase in the opacity cools the star and expands it, leading to an increase in the mass-loss rate which shortens the AGB lifetime. However, most models computed up until about that time used scaled solar low-temperature opacities that did not reflect the "true" composition of the outer layers. Most AGB star models now include such low-temperature C-rich opacity tables [26, 34 – 36].

The latest theoretical predictions for the *s* process in AGB stars are still, for the most part, based upon older AGB models e.g., [17, 27, 28]. There are exceptions including the models of Cristallo and collaborators that are computed using C-rich and N-rich opacity tables [26]. However the only real uncertainty on the s-process predictions that is introduced by older AGB models is that they likely overestimate the number of thermal pulses and TDU mixing episodes, hence the *s*-process yields from such models are also likely to be overestimated as well. Other model uncertainties, such as our inability to accurately model convection in stellar interiors, plays a much more important role in determining the final *s*-process yields from low and intermediate-mass stars.

4. Observational constraints

The comparison of stellar models with observations of AGB stars and their progeny have allowed for much progress in our understanding of *s*-process nucleosynthesis. For example, the s-process indexes ratios ([hs/ls] and [Pb/hs]) observed in stars are directly related to the neutron exposure [37], the precise measurements of isotopic ratios in stardust grains from C-rich AGB stars constrain the neutron exposure and density [38], the prediction of Rb production in the most massive AGB stars as a consequence of the ^{22}Ne(α,n)^{25}Mg neutron source [16] was recently confirmed by observations of bright, O-rich AGB stars in the Milky Way Galaxy, LMC, and SMC [39]. Likewise, [40] confirmed that the ^{13}C(α,n)^{16}O neutron source is dominant in low-mass AGB stars using *s*-process elements at the Sr, Y, Zr peak. Here we discuss planetary nebulae as an example of a potential constraint for the *s* process in AGB stars.

4.1 The *s*-process in low-metallicity PN

Abundances derived from PN spectra provide a complimentary data set to the abundances derived from the spectra of cool evolved stars. Recent observations have shown that some PNe are enriched in heavy elements that can be produced by the *s*-process including Ge, Se, Kr, Xe, and Ba [43, 41, 44]. Sterling & Dinerstein [41] obtained Se and Kr abundances for 120 Galactic

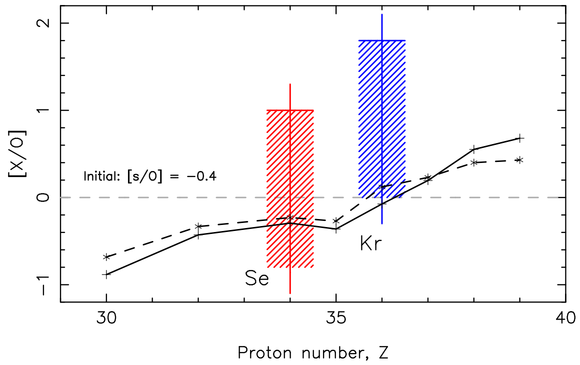

Figure 2: The surface abundances of neutron-capture elements around the first *s*-process peak. The solid lines show results for the $1.25M_{\odot}$, [Fe/H]$= -2.3$ model (solid line), and the $2M_{\odot}$, [Fe/H]$= -2.3$ model (dashed line). An α-enhanced initial abundance pattern was used (e.g., [O/Fe] = $+0.4$), and scaled solar for elements heavier than iron. Abundances are taken at the tip of the TP-AGB after the last computed thermal pulse. The boxes represent the range of observed Se and Kr abundances for the full PN sample from [41]. Figure from [42].

PNe and investigated trends between *s*-process enrichments and PN morphology and other nebular and stellar characteristics. In [17] we compared nucleosynthesis predictions from models of intermediate-mass AGB stars to the results of [41], and in [42] we presented results for lower mass and lower metallicity AGB stars. Recently, [44] obtained *s*-process abundances for the metal-poor BoBn1, showing that the PN is highly enriched in Kr, Xe, and Ba, as well as the light-element F. Fluorine is predicted to be highly enriched in carbon enhanced metal-poor (CEMP) stars that show *s*-process element enhancements as a consequence of binary mass transfer from a former AGB companion [45]. Fluorine enrichment has been found in only a handful of CEMP stars [46] including HE 1305+0132 at a level of [F/Fe] ≈ 2.90 [47] (although see discussion in [46] regarding the uncertainty of the Fe and F abundance of this object).

In Fig. 2 we show the *s*-process abundance distribution for two low-metallicity, low-mass AGB models. For these models we choose an initial α-enhanced abundance pattern (e.g., [O/Fe] $= +0.4$), which results in initial heavy element abundances with [X/O] $= -0.4$ when measured relative to oxygen. In Fig. 2 we also include the Se and Kr abundance distribution from the Sterling & Dinerstein sample, noting that the sample consists of Galactic PNe with higher metallicities than used in the AGB models presented here (we refer to [42] for discussions of the data compared to AGB models of the same metallicity). Low-metallicity models were chosen to highlight the problems with the use of O as a reference element for metallicity. While some PNe in the [41] sample have Ar as a reference, O is more commonly used.

From Fig. 2 the relative ratio of Zn/O is sub-solar, with [Zn/O] ~ -1 (starting at [Zn/O] $= -0.4$) from both models. If we examine the oxygen abundance, we find that a significant amount of this element is dredged to the surface, that is, [O/Fe] ~ 1 for both models. In both cases, Zn is actually produced by the *s*-process but in smaller quantities to oxygen, hence the [X/O] ratios do not reflect the degree of production ([Zn/Fe] ~ 0.4).

For the lowest metallicity PNe, the dredge-up of oxygen implies that this element is no longer a suitable proxy for the initial metallicity of the progenitor star. Argon is sometimes used in place of oxygen, under the assumption that it remains unchanged by AGB nucleosynthesis. Zinc is also another potentially useful reference element, however, as Zn is at the beginning of the *s*-process chain it can be produced in observable quantities in low-metallicity AGB stars.

5. The *s* process in primordial low-mass giant stars

In this last section we outline a new potential site for the occurrence of the *s* process in nature. Models of primordial and hyper-metal poor stars that have masses similar to the Sun are known to experience an ingestion of protons into the core during He ignition (the core He-flash) [48 – 52]. This gives rise to further nucleosynthesis including the production of heavy elements [53], and is qualitatively comparable to the ingestion of protons that occurs in the convective pulse of AGB stars of low metallicities. Using a $1M_{\odot}$ model star with [Fe/H] $= -6.5$, it was found that the ingestion of protons into the hot convective core leads to the production of ^{13}C (protons are captured by the abundant ^{12}C). Subsequent α captures via the ^{13}C$(\alpha,n)^{16}$O reaction leads to the release of free neutrons. The neutrons are then captured by Fe to form heavy elements. Note that while most of the Fe initially present in the star is destroyed by neutron captures, the final Fe abundance is ~ 2.5 dex higher as a consequence of neutron capture on light elements such as C and O. Prodigious amounts of heavy elements are produced and the neutron exposure is $\approx 10^2$ mbarn^{-1}. The final Sr, Ba, and Pb abundances in the core are found to be of the order of the solar abundances. These nucleosynthetic products are later mixed to the surface and ejected by stellar winds. [53] compared the theoretical predictions of their model to the composition of HE 1327-2326, one of the most metal-poor stars known and the only hyper metal-poor star with heavy element abundances [54]. The model was able to self-consistently explain the C, N, O, and Sr abundance of the star, within a factor of four, although it overproduced the Ba abundance. To explain the abundance of HE 1327-2326 it is assumed that system was in a wide binary and that only a small fraction of the mass lost from the model star was accreted onto the donor (the star we observe today). If this scenario is correct, binary systems of low mass must have formed in the early Universe. If this were indeed the case these nucleosynthesis sites would provide a new and unique constraint on the initial mass function of the most metal-poor stars in the Universe.

6. Summary

The AGB phase is the last nuclear burning phase for stars with initial masses between about $0.8M_{\odot}$ to $8M_{\odot}$ and is where the richest nucleosynthesis occurs. The nucleosynthesis is driven by thermal instabilities of the He-burning shell, where the products are dredged to the stellar surface by recurrent mixing episodes. Hot bottom burning occurs in the most massive AGB stars, and this also alters the surface composition. AGB stars are important factories for producing many elements including carbon, nitrogen, fluorine, and heavy elements synthesized by the *s* process. It is estimated that up to half of all elements heavier than iron are made by the *s*-process in low-mass AGB stars.

In these proceedings we have reviewed the *s* process in AGB stars. While much is known about the inner workings of AGB stars, there are many unknowns that render predictions uncertain. In particular, our lack of knowledge about convective mixing processes in stars is perhaps the

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greatest uncertainty, since it overshadows so much of AGB evolution including the formation of ^{13}C pockets and is the main site of the *s* process in the Universe. Other modelling uncertainties are also important for setting the level of chemical enrichment expected from AGB stars including mass-loss rates, opacities, and reaction rates.

Observations of heavy element abundances in AGB stars and their progeny can provide valuable constraints on stellar nucleosynthesis. It is also essential that we understand nucleosynthesis in low-metallicity AGB stars if we are to unravel the puzzle surrounding the abundances of many carbon-rich metal-poor stars in the Galaxy. The mass-transfer processes that occur in binary star systems are poorly understood and these need to be untangled. The origin of the heavy element abundances in globular cluster stars may also require an *s* process contribution from low-metallicity intermediate-mass AGB stars. Indeed, the contribution from such stars is still largely unknown, especially at the lowest metallicities. Finally, new sites for the production of heavy elements may exist, such as the dual core-flash in primordial low-mass giant stars. These theoretical calculations not only challenge our notions about the origin of heavy elements at the earliest times in the Universe but also sets important constraints on the formation of the first stars.

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