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# Stellar yields for chemical evolution modelling

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**Abstract.** Stellar yields are a key ingredient in chemical evolution models. Stars with masses as low as $0.9M_{\odot}$, which have an age less than that of our Galaxy at low metallicity, can contribute to the chemical evolution of elements. Stars less than about 8–$10M_{\odot}$ experience recurrent mixing events that can significantly change the surface composition of the envelope. Evolved stars are observed with surface enrichment in carbon, nitrogen, fluorine, and heavy elements synthesized by the slow neutron capture process (the *s*-process). These stars release their nucleosynthesis products through stellar outflows or winds, in contrast to massive stars that explode as core-collapse supernovae. Here I review stellar yields for stars up to $10M_{\odot}$, including a brief discussion of their uncertainties and shortcomings. Finally, I discuss efforts by various groups to address these issues and to provide homogeneous yields for low and intermediate-mass stars covering a broad range of metallicities.

**Keywords.** stars: AGB and post-AGB – stars: Population II – ISM: abundances – Galaxy: abundances

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## 1. Introduction

Low to intermediate-mass stars are a common constituent of galaxies, partly because they span a range in mass from about $0.8M_{\odot}$ to $\sim 8M_{\odot}$ but also because of their relatively long lifetimes. These stars evolve through core hydrogen burning on the main sequence, through the first giant branch, and onto the final nuclear burning phase in the core where helium is converted into carbon. After core helium exhaustion, low and intermediate-mass stars evolve up the giant branch for the second and final time. Stars are now on the asymptotic giant branch or AGB. The AGB is brief, lasting less than 1% of the main sequence lifetime. Because the number of stars in any phase of the Hertzsprung-Russell (HR) diagram is proportional to lifetime, there are not many AGB stars in any particular colour-magnitude diagram but thankfully they are easy to detect, owing to their high luminosities and often very red colours. The red colours arise because of intense mass loss, which removes the outer envelope and will eventually cause the star to leave the AGB altogether, evolving through the post-AGB phase before becoming a white dwarf. Many AGB stars are observed to be chemically different from their less evolved counterparts and show enrichment in carbon, fluorine, and heavy elements synthesized by the *slow* neutron capture process (the *s*-process; see review by Busso *et al.* 1999). In particular, AGB stars can become C-rich where the C/O ratio exceeds unity. The intense mass loss from AGB stars enriches the interstellar medium with the products of their nucleosynthesis which has been subjected to hydrogen and helium-burning as well as neutron-capture nucleosynthesis. Owing to their large numbers and rich nucleosynthesis, AGB stars are important contributors to the chemical evolution of elements in our Universe (e.g., Travaglio *et al.* 2001; Romano *et al.* 2010; Kobayashi *et al.* 2011; Hansen *et al.* 2013).

In the following proceedings we will define low-mass stars as those with masses up to about $4M_\odot$ and intermediate-mass stars as those with masses between about $4$–$8M_\odot$. These mass distinctions arise because of the type of mixing and nucleosynthesis that occurs on the AGB and will be discussed below. The upper mass limit of $8M_\odot$ (at $Z = 0.02$) is the maximum initial stellar mass for producing a C-O core white dwarf. Stars more massive than this go through central carbon burning. In particular, stars in the mass range from about $8$–$10M_\odot$ evolve through off-centre degenerate central carbon burning. These stars may also experience thermal instabilities in their helium burning shells and become super-AGB stars with O-Ne-Mg cores (Ritossa *et al.* 1996, 1999).

Stellar yields are a vital ingredient of chemical evolution models. Up until 2007 the only stellar yields for AGB stars were calculated from synthetic AGB models or from a combination of detailed models and synthetic (van den Hoek & Groenewegen 1997; Forestini & Charbonnel 1997; Marigo 2001; Izzard *et al.* 2004). Synthetic AGB models are produced using fitting formulae (e.g., core-mass–luminosity relation) that are themselves derived from more detailed models that solve the equations of stellar structure. Karakas & Lattanzio (2007) published the first set of stellar yields from detailed stellar evolutionary models, with an update by Karakas (2010). While these AGB yields have their limitations, these data are still the largest and most complete yield database available, even if they do not include super-AGB stars or yields of *s*-process elements.

In this review we focus on theoretical models of stars up to about $9$–$10M_\odot$ and in particular on recent progress in calculating AGB yields. In the context of this particular meeting, the stellar yields and theoretical models are needed to help interpret the wealth of observational data that will come from current and future surveys such as the Gaia-ESO Survey, GALAH using HERMES on the AAT, APOGEE, and LAMOST. These surveys will obtain stellar abundances for many elements for a vast numbers of stars in our Galaxy. These data-sets will include elements produced primarily by AGB stars including carbon and heavy elements produced by the *s*-process (e.g., yttrium, strontium, barium).

## 2. Stellar evolution through the giant branches

All stars begin their nuclear-burning life on the main sequence, burning hydrogen to helium in their cores. Following core H exhaustion the core contracts and H burning is established in a shell as the star crosses the Hertzsprung Gap. The outer layers of the star expand, the core shrinks and convection moves inwards for the first time. The star is now on the red giant branch (RGB) and the first changes to the surface composition occur as the products of H burning are dredged to the surface by convection. The most striking observable change is a reduction in abundance of $^{12}$C from CN cycling, which results in decreases in the C/N and the $^{12}$C/$^{13}$C ratios (e.g., Boothroyd & Sackmann 1999). The first dredge up (FDU) leaves behind a sharp composition discontinuity exterior to the position of the H-burning shell. It is after this discontinuity is erased (the luminosity bump on the giant branch) that "extra-mixing" may occur. Observational evidence for extra mixing and the latest theoretical models are discussed in §2.2.

During the ascent of the RGB, the He cores of low-mass stars contract and heat and eventually become electron degenerate. The RGB lifetime is terminated when the temperature reaches about 100 million K and the triple-alpha reactions are ignited. The temperature and density are essentially decoupled and this leads to a violent helium ignition that is referred to as the core helium flash. The maximum initial mass for the

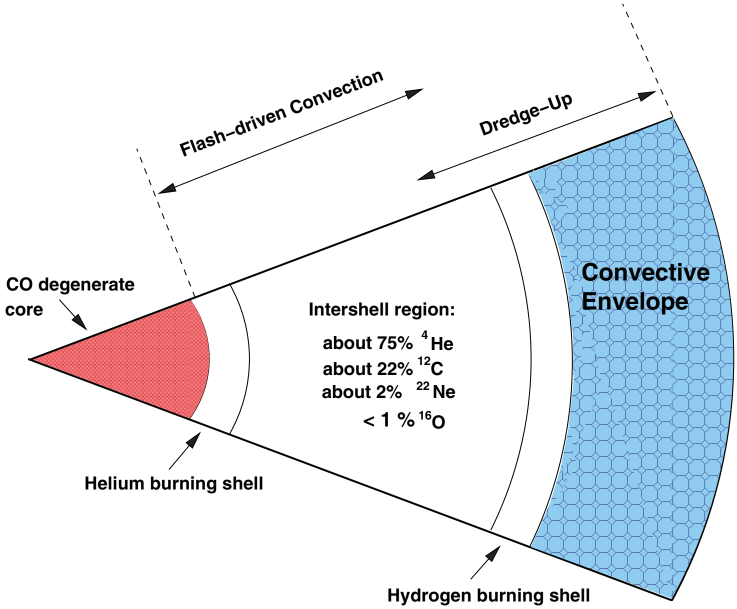


**Figure 1.** Schematic structure of an AGB star. It is the intershell region that the *s*-process occurs. The figure is not to scale. From Karakas, Lattanzio, & Pols (2002).

core He-flash to occur is $\approx 2\mathrm{M}_\odot$ at solar metallicity. Following the core He flash, the star settles down to a period of quiescent core He-burning. In stars with masses $M \gtrsim 2\mathrm{M}_\odot$, depending on metallicity, $Z$, the contracting He cores do not become electron degenerate and the ignition of He occurs non-degenerately. The properties of the C-O core left after core He-burning depends on a number of uncertainties including the amount of core overshoot and the rate of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction (e.g., Imbriani *et al.* 2001).

Following core He exhaustion the star becomes a giant for the second time. The strong expansion of the star caused by the structural re-adjustment to He-shell burning causes the H-shell to be extinguished following core helium exhaustion. With the entropy barrier of the H-shell gone, the convective envelope moves inward. In low-mass stars the envelope does not penetrate as deeply as it did on the RGB. In intermediate-mass stars this inward movement results in the second dredge-up and is predicted to be the most important change to the surface composition prior to the AGB. Large increases in helium (up to $\Delta Y \approx 0.1$) and $^{14}\mathrm{N}$ are predicted. There is a critical minimum mass below which the SDU does not occur ($\approx 4.5\mathrm{M}_\odot$ at $Z = 0.02$; Karakas 2010). Once the first He-shell instability occurs the star is now said to be on the thermally-pulsing AGB (TP-AGB) where the structure is qualitatively the same for all masses (Figure 1).

At low metallicity ($Z \leqslant 0.001$) stars over about $3\mathrm{M}_\odot$ do not experience a first red giant phase as they ignite helium in their cores after they cross the Hertzsprung gap. The surface composition of these stars is not altered by the FDU and the first mixing event to shape the composition of the envelope is instead the second dredge up (SDU), which takes place after core helium burning.

The structure of an AGB shown in Figure 1 has two burning shells, one burning H into He, and another burning He into C. The He-burning shell is thermally unstable and flashes or pulses for a brief period ($\approx 10^2$ years) during which an enormous amount of energy is produced (up to $10^8 L_\odot$). In-between thermal pulses ($\approx 10^5$ years depending on H-exhausted core mass) the hydrogen burning shell provides most of the surface luminosity (for a review see Herwig 2005). The large burst of energy from the thermal pulse drives a convective zone in the intershell, which homogenizes the products of He-nucleosynthesis throughout the region. Most of the energy from the thermal pulse does not reach the stellar surface but is instead converted into mechanical energy where it expands the whole star. The expansion essentially extinguishes the H-shell and allows the convective envelope to move inwards. If the convective envelope reaches the intershell, then third dredge up (TDU) is said to have occurred. The TDU is responsible for enriching the surface in $^{12}$C and other products of helium burning and the *s*-process. Following TDU the star contracts and the H-shell is re-ignited, providing most of the surface luminosity during the next interpulse period. The cycle of interpulse–thermal pulse–dredge-up may occur many times on the AGB. The number of thermal pulses is dependent on stellar parameters (initial mass, core mass, metallicity) and on the mass-loss rate during the AGB.

In intermediate-mass AGB stars ($M \gtrsim 4\mathrm{M}_\odot$) the convective envelope dips into the top of the H-shell, resulting in nuclear burning at the base of the convective envelope (e.g., Lattanzio 1992). This phenomena is known as hot bottom burning (HBB) and can dramatically alter the surface composition. The TDU may still occur in these stars which can lead to a significant amount of primary $^{14}$N production (Pols *et al.* 2012). This is because TDU mixes primary $^{12}$C from the He-burning shell to the envelope; from there it is efficiently converted to nitrogen by the CNO cycle. Higher-order hydrogen burning may also occur, converting neon to sodium and magnesium to aluminium (e.g., Karakas & Lattanzio 2003b). Other products of helium-shell burning may include the neutron-rich Mg isotopes (e.g., Karakas & Lattanzio 2003a; Fenner *et al.* 2003). Intermediate-mass stars enter the AGB with H-exhausted core masses $\gtrsim 0.8-1.2\mathrm{M}_\odot$ and evolve more rapidly than their lower mass counterparts. Indeed, they may evolve so rapidly during the brief post-AGB phase that it is unlikely that they will have time to ionize the surrounding medium and become planetary nebulae.

In summary, the stellar yields from low-mass stars with masses up to about $4\mathrm{M}_\odot$ are shaped by the action of the FDU, which takes place after the main sequence, and TDU, which takes place during the AGB. Stars on the AGB are predicted (and observed) to become carbon, fluorine, and *s*-process rich and to release vast quantities of gas and dust to the ISM. In contrast, the stellar yields of intermediate-mass stars are influenced by SDU, after core helium burning, and then the complex interplay between TDU and HBB during the AGB. HBB can prevent the formation of a C-rich atmosphere, although there is a strong metallicity dependence where metal-poor intermediate-mass stars can become C-rich at the tip of the AGB (e.g., Frost *et al.* 1998). The yields are dominated by hydrogen burning products (e.g., helium, nitrogen, sodium) as well as helium-shell burning products (e.g., $^{25}$Mg, $^{26}$Mg) depending on the efficiency of TDU.

### 2.1. *Uncertainties*

AGB nucleosynthesis depends on the initial stellar mass and metallicity, which in turn determine the efficiency of the TDU, the minimum core mass for the onset of TDU episodes, and on minimum stellar mass for the onset of HBB. For this reason yields of AGB stars need to cover a large range of initial mass and metallicity to sample the range of possible nucleosynthesis outcomes (e.g., the integrated nitrogen yield is extremely dependent on the minimum initial mass for HBB, which needs to be accurately determined). Furthermore, mixing in AGB envelopes depends critically on the treatment of convection used in stellar interiors, and on our ability (or lack thereof) to determine the border between a radiative and convective region (Frost & Lattanzio 1996; Mowlavi 1999; Herwig 2000; Ventura & D'Antona 2005a). For example, some codes do not find any TDU without

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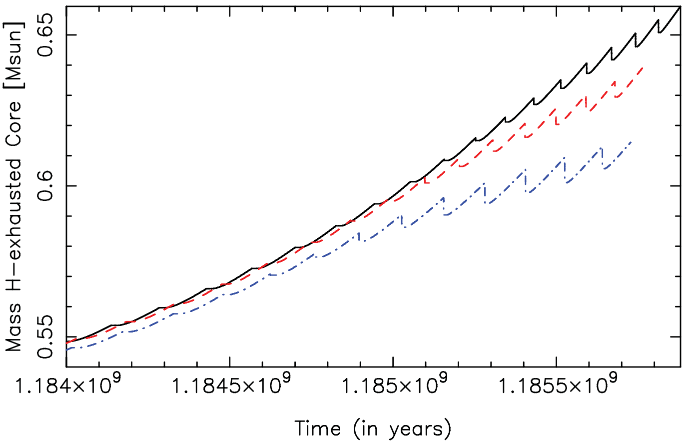


**Figure 2.** Evolution of the hydrogen-exhausted core as a function of time for a series of models of the same mass ($2M_\odot$) and composition ($Z = 0.014$, solar) but with different amounts of convective overshoot. The black solid line shows the model with no convective overshoot, which still experiences some third dredge-up, the red dashed line with a small amount of overshoot where the base of the convective envelope is extended by 1 pressure scale height beyond the formal convective-radiative boundary, and the blue dot-dashed line with a more moderate amount, where the base of the convective envelope has been extended by 2 pressure scaled heights. More overshoot leads to a lower final remnant mass and a stronger enrichment of the envelope. The amount of overshoot can be constrained by studying AGB stars in clusters (e.g., Kamath *et al.* 2012). For the case of $2M_\odot$, $Z = 0.014$ model considered here, the model with the most overshoot gives the best match to the final masses of the white dwarfs in the Galactic open cluster NGC 7789. The average white dwarf mass in NGC 7789 is $0.61M_\odot$ and the estimated initial mass is $2M_\odot$ (Kalirai *et al.* 2008).

the inclusion of convective overshoot (Mowlavi 1999), or enough TDU to account for the existence of low-mass carbon stars (Karakas *et al.* 2002). In Figure 2 we show an example of the differences in the evolution of the H-exhausted core mass with different amounts of convective overshoot for a model of $2M_\odot$, $Z = 0.014$ (solar metallicity). The model with the most overshoot has deeper TDU and dredges up about twice as much He-intershell material as the model with no overshoot. The amount of overshoot now becomes another uncertain parameter that needs to be set (e.g., by using AGB stars in star clusters; Kamath *et al.* 2012). The occurrence of TDU in intermediate-mass AGB models is also considered uncertain, at least at low metallicities (Ventura & D'Antona 2005a). However, at the metallicities of the Galaxy and the Large and Small Magellanic Clouds there is evidence for TDU in the brightest AGB populations (Frost *et al.* 1998; van Loon *et al.* 1999; García-Hernández *et al.* 2006). More observations would help settle this discussion but unfortunately metal-poor intermediate-mass stars have long evolved away. Mass loss terminates the AGB phase and determines the number of thermal pulses and mixing episodes, as well as the duration of HBB (Ventura & D'Antona 2005b; Stancliffe & Jeffery 2007; Karakas *et al.* 2012). Other uncertainties include thermonuclear reaction rates which can be highly uncertain at stellar temperatures (Ventura & D'Antona 2005b; Karakas *et al.* 2006; Izzard *et al.* 2007).

Marigo (2002) showed that inclusion of C-rich low-temperature opacities is an important addition to the modelling of TP-AGB stars. That is because the C dredged into the envelope forms C-bearing molecules (e.g., CO, CN) which lead to a strong increase in the stellar opacity. The increase in the opacity cools the star and expands it, leading to an increase in the mass-loss rate which consequently shortens the AGB. A shorter AGB

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lifetime means less mixing episodes and a lower level of chemical enrichment. The opacity tables of Lederer & Aringer (2009) and Marigo & Aringer (2009) are now routinely used in stellar evolutionary codes used to calculate AGB models (Cristallo *et al.* 2009; Weiss & Ferguson 2009; Ventura & Marigo 2009; Karakas *et al.* 2010; Ventura & Marigo 2010; Kamath *et al.* 2012; Karakas *et al.* 2012).

### 2.2. *Extra mixing in low-mass giant stars*

There is considerable evidence for some type of non-convective extra mixing process (or processes) occurring in the envelopes of low-mass giant stars (e.g., Gilroy 1989; Smiljanic *et al.* 2009). Data exists for stars in Galactic open clusters (Gilroy 1989) as well as for stars in metal-poor globular clusters (Smith 2002; Lind *et al.* 2009). The situation for AGB envelopes is more ambiguous, especially at disk metallicities which show $^{12}C/^{13}C$ ratios at about the level expected from extra-mixing on the RGB alone (e.g., Karakas *et al.* 2010). Evidence for deep mixing on the AGB comes mainly from oxygen and aluminium isotope ratios measured in pre-solar oxide grains but also C-stars that show very low $^{12}C/^{13}C$ ratios (Abia & Isern 1997; Busso *et al.* 2010). At lower metallicities, evidence for extra mixing in AGB stars becomes stronger, where carbon-enhanced metal-poor stars show enhanced nitrogen and low $^{12}C/^{13}C$ ratios (e.g., Beers & Christlieb 2005; Sivarani *et al.* 2006), in contrast to standard stellar evolutionary AGB models (Karakas 2010; Lugaro *et al.* 2012).

The mechanism responsible for the extra mixing is not known but a few physical mechanisms have been proposed including meridional circulation caused by rotation (Sweigart & Mengel 1979), magnetic fields (Busso *et al.* 2007), and mixing caused by molecular weight inversions (also known as thermohaline mixing; Eggleton *et al.* 2006; Charbonnel & Zahn 2007; Denissenkov & Pinsonneault 2008; Stancliffe *et al.* 2009; Stancliffe 2010; Angelou *et al.* 2012; Lagarde *et al.* 2012a). Some algorithms used in extra mixing models are parametrised to reproduce the observed data (Smith & Tout 1992; Charbonnel 1995; Boothroyd & Sackmann 1999; Denissenkov & Tout 2000). The depth and temperature to which the material is mixed, along with the amount of material in the circulation current are free parameters that are constrained to fit the observed abundances (see also Nollett *et al.* 2003; Palmerini *et al.* 2009).

The effect of extra mixing on the stellar yields is mostly on the light elements $^{3}$He, lithium (Lagarde *et al.* 2012b), and on the $^{12}C/^{13}C$ isotope ratios, and nitrogen. Extra mixing is predicted to reduce the $^{3}$He abundance, and increase the abundances of $^{13}$C and $^{14}$N in the interstellar medium. Stellar yields from AGB models with extra mixing are not widely available yet although Lagarde *et al.* (2012a) include two TP-AGB stars in their grid.

### 2.3. *Super-AGB stars*

Stars in the mass range $\approx 8M_\odot$ to $10M_\odot$ (at $Z = 0.02$) evolve through off-centre degenerate carbon burning and may experience thermal instabilities during the AGB. These stars have an electron-degenerate O-Ne core, but otherwise their structure is predicted to be much like that shown in Figure 1. It is still not known what fraction of super-AGB stars leave behind a massive O-Ne white dwarf or explode as electron capture supernovae (Nomoto 1984; Poelarends *et al.* 2008). Super-AGB stars are predicted to experience very hot proton-capture nucleosynthesis at the base of the convective envelope (where $T > 10^8$K) and may also experience TDU mixing from the He-shell. Furthermore, super-AGB stars are also predicted to experience a deep second dredge-up, where the convective envelope mixes into the He-burning shell while it is still active (known as “dredge-out”, see Ritossa *et al.* 1996, 1999).

Recent efforts to study various aspects of super-AGB stars and their subsequent fate include Gil-Pons *et al.* (2005), Siess (2006), Gil-Pons *et al.* (2007), Siess (2010), Pumo *et al.* (2008), Doherty *et al.* (2010), Karakas *et al.* (2012), Herwig *et al.* (2012), and Takahashi *et al.* (2013). The only grids of super-AGB yields currently published are by Siess (2010) and show these stars to be producers of hydrogen-burning products owing to their very hot HBB. If super-AGB stars experience TDU then they may also produce heavy elements by the slow neutron capture process (Karakas *et al.* 2012). There have also been suggestions that electron-capture supernovae from O-Ne core AGB stars may also produce heavy elements via the rapid neutron capture process (Wanajo *et al.* 2009, 2011).

### 2.4. *The slow neutron capture process*

One unmistakable signature of AGB nucleosynthesis is the $s$-process. This is the production of elements heavier than iron by neutron capture reactions in the deep interior of AGB stars. Observational evidence for this has been around since 1952 when Merrill (1952) discovered AGB stars with enhancements in the radioactive element Tc. Since then there have been numerous observations of $s$-process rich AGB stars covering a large range in mass and metallicity (e.g., Smith & Lambert 1989, 1990; Abia *et al.* 2001; García-Hernández *et al.* 2006, 2009). Enrichment in heavy elements have also been confirmed in the progeny of AGB stars: post-AGB stars and planetary nebulae (van Winckel 2003; Sterling & Dinerstein 2008; De Smedt *et al.* 2012). Given space restrictions, we refer to Busso *et al.* (1999) and Lattanzio & Lugaro (2005) for an indepth review of the $s$-process in AGB stars. Sneden *et al.* (2008) summarizes the situation for neutron-capture elements in the early Galaxy.

Chemical evolution models that include the $s$-process (Travaglio *et al.* 2001, 2004) show that AGB stars have an important impact in the production of heavy elements. However, stellar yields that include the $s$-process are even more sparse than those for lighter elements. This means that one large uncertainty still exists today for chemical evolution modellers: There are no grids of $s$-process yields available for stars of $M = 1\mathrm{M}_{\odot}$ to the upper limit of the AGB (6-8$\mathrm{M}_{\odot}$) for a large range of metallicities. Ideally, these grids should also contain light element predictions for self consistency, isotopic yields, and a range of initial assumptions about the size of the $^{13}$C pocket, which determines the level of $s$-process enrichment during the AGB (e.g., Gallino *et al.* 1998), and the initial composition.

## 3. Stellar yields from AGB stars

Stellar yields are a particularly sensitive and uncertain input into chemical evolution models (Romano *et al.* 2010). The publication of the first detailed yields from low and intermediate-mass stars by Karakas & Lattanzio (2007) covered a range in mass from $M = 1\mathrm{M}_{\odot}$ to $6\mathrm{M}_{\odot}$ ($6.5\mathrm{M}_{\odot}$ at $Z = 0.02$) and a range of metallicities from $Z = 0.02, 0.008, 0.004$ and 0.0001. As extensive as these yields are, they only include yields of light elements, that is, for elements from hydrogen to sulfur, and then a small-group of iron-peak elements which measure the number of neutron captures taking place. Other groups have since published yields including Siess (2010) who published the first set of yields for super-AGB stars but because his models do not experience any TDU, he synthetically calculated yields with different amounts of TDU. Lagarde *et al.* (2012a) published yields for a large range of stellar masses and metallicities, and studied the effect of non-standard physics such as thermohaline mixing and rotation on the yields. However, only two of those models were evolved through the TP-AGB. Ventura *et al.*

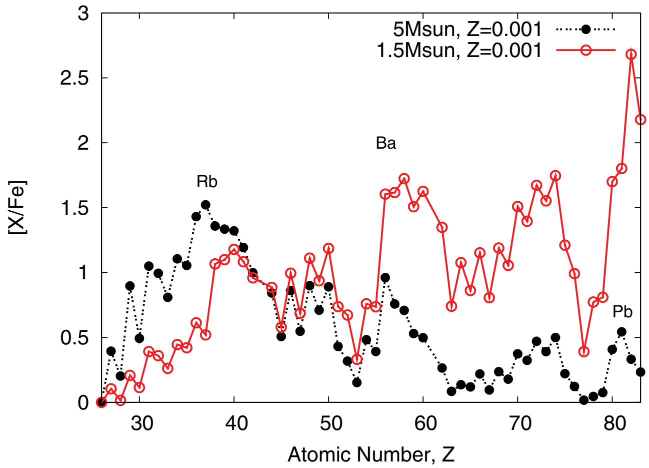


**Figure 3.** Final surface abundances from two AGB models of $Z = 0.001$ ([Fe/H] $= -1.2$). The $1.5M_\odot$ model shows an $s$-process signature typical of low-mass low-metallicity AGB stars, with copious Ba and Pb production. The intermediate-mass AGB star has an $s$-process signature typical of the $^{22}$Ne($\alpha$,n)$^{25}$Mg neutron source which makes copious Rb, with a small amount of second (Ba) and third peak (Pb) element production. The model data are from Fishlock *et al.* (2013, in preparation).

(2013) published yields covering a significant range of mass from $1.5M_\odot$ up to and including super-AGB stars ($6 - 8M_\odot$), for a range of metallicities appropriate for globular clusters. No yields for solar metallicity were included and the yields only included light elements, that is, no $s$-process predictions.

In regard to yields including $s$-process elements, Cristallo *et al.* (2011) published the FRUITY database which includes yields for a full network from hydrogen to bismuth, for a range of stellar masses up to $3M_\odot$ and metallicities from solar to $Z = 0.001$ (or [Fe/H] $= -1.2$). Lugaro *et al.* (2012) published stellar abundance predictions for a range of stars from $0.9M_\odot$ to $6M_\odot$ at $Z = 0.0001$ ([Fe/H] $= -2.3$) for a full nuclear network. These and the study by Karakas *et al.* (2012) are the only full $s$-process yields currently published for intermediate-mass AGB stars with masses above $3M_\odot$. Fishlock *et al.* (2013, in preparation) is publishing stellar yields for all stable elements from $M = 1 - 7M_\odot$ AGB models. A sample of those results are shown in Fig. 3. This figure illustrates the striking difference between the $s$-process yields of low-mass AGB stars and intermediate-mass AGB stars and demonstrates the need for yields that cover a large range in mass.

## 4. Summary and outlook

In these proceedings we have examined the current status of stellar yields from AGB evolutionary models. 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. It is during the AGB when stars shed much of their outer envelopes to the interstellar medium, making these objects important sources of dust and gas in galaxies.

We have shown that stellar yields from AGB stars of all mass ranges are being calculated and published. There are still significant gaps, especially for elements produced by the slow neutron capture process and for the most massive AGB stars. Many significant uncertainties affect the stellar yield calculations, such as convection and mass loss, and these in turn affect the accuracy and reliability of chemical evolution model predictions. Non-standard physics such as rotation and thermohaline mixing are now starting to be included into stellar evolutionary calculations and the first yields are appearing, showing that these mechanisms have an important impact on the evolution of some elements. In the future these mechanisms will have to become standard, and we need to understand their impact on the nucleosynthesis of elements from hydrogen through to lead. We still have some ways to go here!

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## Discussion

Eline Tolstoy: Can horizontal branch morphology be used to constrain mass loss in (low-mass) AGB stars?

Amanda Karakas: Quite possibly, if there are good data for stars in clusters where there is a known turn off mass.

Eline Tolstoy: Can you explain helium in galactic globular clusters?

Amanda Karakas: Intermediate-mass AGB stars produce significant quantities of helium from the second dredge-up, which takes place before the thermally-pulsing AGB phase. The amount of helium produced is usually on the order of $\Delta Y \approx 0.1$, so starting at $Y = 0.25$ produces enough helium to explain all but the most enriched clusters like NGC 2808. If $Y$ of 0.4 is needed then it is hard to see how that could come from an AGB star.

Johannes Andersen: Comment: The "peculiar" C-enhanced extremely metal-poor stars are still $20 - 40\%$ of the EMP stars below $[Fe/H] < -3$ in the halo!

Amanda Karakas: Yes, it is true they are not so peculiar, especially at the lowest metallicities. However at disk metallicities barium and CH stars make up only 1% of all giants, and we don't quite yet know how to go from such a low fraction to $\geqslant 20\%$ although Izzard *et al.* (2009) tried using binary population synthesis models. This model was based on AGB mass transfer whereas we know that at the lowest metallicities the carbon is probably coming from core collapse supernovae.

Bacham E. Reddy: How is Li production and RGB luminosity bump possibly related? Also quite a few stars that are Li rich at the bump show a dust signature. If this is true, the RGB bump could be a significant source of Galactic Li?

Amanda Karakas: Standard low-mass stellar evolution models do not predict Li production at the RGB bump. Observations show that that Li production is happening but the mechanism is not at all understood. Regarding the RGB bump as an important Galactic source of Li, it is true that Prantzos (2012) has shown that there must be an important stellar component to Li production. We don't know where that is coming from (low mass stars with extra mixing? HBB stars?). If it is coming from the RGB bump then there should be significant mass loss observed there.

Filippo Fraternali: What are the most recent estimates for the returned fraction, i.e., the fraction of mass that is returned to the ISM by stellar evolution?

Amanda Karakas: The amount of mass returned from a population of AGB stars is relatively robust, and is not greatly dependent on stellar modelling uncertainties such as convection or mass loss. It is somewhat sensitive to the initial-final mass relation but uncertainties stemming from the shape of the initial mass function is a far more serious uncertainty.