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The role of asymptotic giant branch stars in galactic chemical evolution

A. I. Karakas

Research School of Astronomy and Astrophysics, the Australian National University, Canberra, ACT 2611, Australia, e-mail: amanda.karakas@anu.edu.au

Abstract. The chemical evolution of the Universe is governed by the nucleosynthesis output from stars, which is determined primarily by the initial stellar mass. Stars less massive than about 8–10$M_{\odot}$, depending on metallicity, experience recurrent mixing events on the giant branches that can significantly change the surface composition of the envelope, with observed enrichments in lithium, carbon, nitrogen, fluorine, and heavy elements synthesized by the slow neutron capture process (the *s*-process). It is during the asymptotic giant branch (AGB) phase of stellar evolution when the richest nucleosynthesis occurs. This phase is also characterized by intense mass loss, which releases the nucleosynthesis products into the interstellar medium. The stellar yields available for single stars with masses up to about 10$M_{\odot}$ are reviewed, along with a broader discussion of the role that AGB stars play in the chemical evolution in galaxies and stellar systems.

Key words. Stars: abundances – Stars: AGB and post-AGB – Stars: Population II – Galaxy: abundances – ISM: abundances

1. Introduction

Stars with initial masses between 0.8 – 8$M_{\odot}$ evolve through core hydrogen and helium burning before ascending the asymptotic giant branch (AGB). Fig. 1 illustrates the approximate mass ranges for AGB stars of solar metallicity ($Z \approx 0.014$). The lower mass limit is the minimum mass for the onset of core helium burning, while the upper mass range defines the onset of core carbon burning. The exact mass range of AGB stars is metallicity dependent, with the minimum mass for core helium/carbon burning decreasing with decreasing metallicity. The AGB phase is the last nuclear burning phase for these low and intermediate-mass stars. The ages of AGB stars vary enormously, with evolved stars of $\approx$ 12 Gyr observable in metal-poor globular clusters. In contrast, young metal-rich stellar populations of $\lesssim$ 100Myr can host AGB stars from the most massive end of the range (up to 8$M_{\odot}$), which includes those stars that are close to or at the core carbon burning limit (e.g., Whitelock et al. 2013).

AGB stars are important for the lives of galaxies because they can produce substantial amounts of the gas and dust (Sloan et al. 2008). AGB stars are especially important for producing carbonaceous dust, with most of the presolar silicon carbide grains forming in the outflows of AGB stars (Zinner 2008, 2014). Galaxies dominated by intermediate-age stellar populations have a significant fraction of their starlight emitted by low and intermediate mass stars, especially when they evolve off the

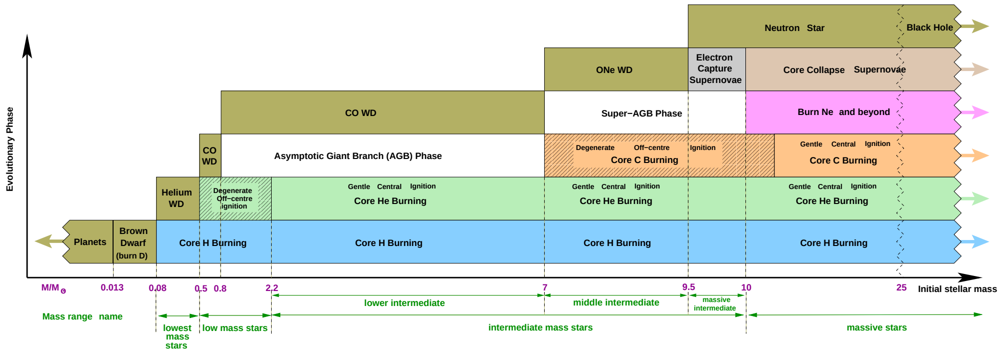

Fig. 1. Schematic showing how stellar mass determines the main nuclear burning phases and the fate of the final remnant for solar metallicity models. The borders are often not well determined and depend on uncertainties (e.g., mass loss, convection) in the modelling process. This is particularly true for the borders around the region of the electron-capture supernovae. From Karakas & Lattanzio (2014).

main sequence to the giant branches (Maraston 2005; Tonini et al. 2009; Melbourne et al. 2012). AGB stars in particular are bright and therefore observable in resolved stellar populations in nearby galaxies (e.g., Boyer et al. 2013; Whitelock et al. 2013).

AGB stars can produce a rich array of nucleosynthesis products including carbon and roughly half of all elements heavier than iron by the slow neutron capture process (the *s* process, e.g., Busso et al. 1999; Travaglio et al. 2001; Herwig 2005; Romano et al. 2010; Kobayashi et al. 2011; Prantzos 2012; Bisterzo et al. 2014). Intermediate-mass stars over about $4M_{\odot}$ experience hot hydrogen burning at the base of their convective envelopes, which produces Li, N, Na and Al. It is for this last reason that intermediate-mass AGB stars have been considered polluters of Galactic globular clusters (e.g., Ventura & D'Antona 2009). Globular clusters show the signature of hydrogen burning through the abundance variations in Li, C, N, O, Na, and even Mg and Al in some clusters (Gratton et al. 2012). Other polluters have been suggested including massive binary stars (de Mink et al. 2009), massive rotating stars (Decressin et al. 2009), and even extremely massive stars (Denissenkov et al. 2015b). However, there are problems associated with each polluting source and currently no satisfactory solution exists. The main issue with AGB stars are the uncertainties inherent in the stellar yields.

Here we review the stellar yields available for AGB stars. Much of what we discuss here has been reviewed in greater detail by Karakas & Lattanzio (2014).

2. AGB evolution

The schematic structure of an AGB star is shown in Fig. 2 and is qualitatively the same for all masses. 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 (hereafter core mass). The energy from the thermal pulse drives a convective zone in the He-rich intershell (which lasts for $\approx 10^2$ years, again depending on core mass), which mixes the products of 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, which may allow 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 may occur after each thermal pulse. TDU is responsible for enrich-

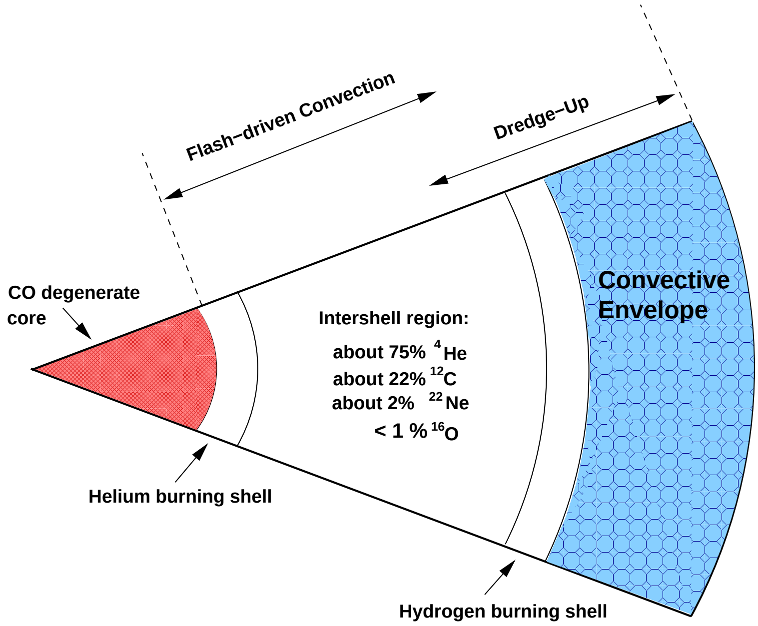

Fig. 2. Schematic structure of an AGB star showing the electron-degenerate C-O core surrounded by a helium-burning shell, and a hydrogen-burning shell below the deep convective envelope. The burning shells are separated by an He-rich intershell region. A super-AGB star has an O-Ne degenerate core otherwise the qualitative schematic structure remains the same. From Karakas, Lattanzio, & Pols (2002).

ing the surface in ^{12}C as well as heavy elements produced by the *s* process. Following 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, depending on the initial mass and composition, as well as on the mass-loss rate.

In intermediate-mass AGB stars ($M \gtrsim 4M_{\odot}$ depending on metallicity) the base of the convective envelope can become hot enough ($T \gtrsim 60 \times 10^6$ K) to sustain proton-capture nucleosynthesis. At these temperatures, intermediate-mass AGB can produce Li via the Cameron-Fowler mechanism, and experience hydrogen burning via the CNO cycles and the NeNa and MgAl chains. This leads to the production of N, Na, Al and the destruction of C, O, and possibly Mg. 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 $\approx$ 1 year, which means that the whole envelope will be mixed through the hot region a few thousand times per interpulse period. TDU may still occur in these stars, which can lead to the production of primary nitrogen and a strong increase in the total C+N+O content of the envelope.

Calculations of AGB stars over the last ~ 5 years have explored updated input physics (e.g., low temperature opacities), rotation, extra mixing, and/or an extended range of the mass and metallicity parameter space (e.g., Weiss & Ferguson 2009; Cruz et al. 2013; Constantino et al. 2014; Gil-Pons et al. 2013; Cristallo et al. 2009, 2011; Kamath et al. 2012; Karakas et al. 2014; Karakas 2014; Fishlock et al. 2014b,a; Shingles et al. 2015; Pignatari et al. 2013; Piersanti et al. 2013; Straniero et al. 2014; Lagarde et al. 2011, 2012; Charbonnel & Lagarde 2010; Stancliffe 2010; Ventura & Marigo 2009, 2010; Ventura et al. 2013).

The final fate of a low and intermediate-mass star is to become a C-O white dwarf with a mass in the range 0.55 to $1.1 M_{\odot}$, with a sharp peak at $0.6 M_{\odot}$ (Ferrario et al. 2005; Kalirai et al. 2008). Intermediate-mass stars enter the TP-AGB with core masses $\gtrsim 0.8 - 1.1 M_{\odot}$ and will evolve more rapidly than their lower mass counterparts (e.g., Vassiliadis & Wood 1994). 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.

Stars with masses above about $8 M_{\odot}$ will experience core carbon burning before ascending the AGB phase. These stars are known as super-AGB stars and have a similar schematic structure as shown in Fig. 2 except that they have an electron-degenerate O-Ne core, possibly with some carbon remaining, surrounded by two burning shells and a deep, H-rich convective envelope. There are an increasing number of papers detailing calculations of super-AGB stars, which are time consuming and difficult to model (Siess 2007, 2010; Doherty et al. 2010, 2014a,b, 2015; Jones et al. 2013, 2014; Karakas et al. 2012; Takahashi et al. 2013; Ventura & D'Antona 2011; Ventura et al. 2012).

The final fates of super-AGB stars are unknown but most likely end up as massive O-Ne white dwarfs, which may explode as O-Ne novae or unusual Type Ia supernova known as Type Iax (Denissenkov et al. 2015a; Kobayashi et al. 2015). A small fraction may explode as electron-capture supernova if they reach $1.37 M_{\odot}$ (Jones et al. 2014; Doherty et al. 2015; Takahashi et al. 2013). One important nucleosynthesis outcome associated with electron-capture supernovae is the rapid neutron capture process (the *r* process, Wanajo et al. 2011).

3. Stellar yields

Stellar yields are an essential ingredient of chemical evolution models. Prior to 2001, the only stellar yields available for low and intermediate-mass stars were for synthetic AGB evolution models or from a combination of detailed and synthetic models (e.g., Renzini & Voli 1981; van den Hoek & Groenewegen 1997; Forestini & Charbonnel 1997; Marigo 2001; Izzard et al. 2004; Gavilán et al. 2005). The distinction between synthetic and detailed is that synthetic models use fitting formulae to crudely follow the evolution of a star, albeit very quickly. In contrast, detailed models solve the equations of stellar structure from the main sequence to near the tip of the AGB. However, some of the input physics may be the same, such as AGB mass loss which is itself parameterized from observations and theory. Note that the `COLIBRI` code (Marigo et al. 2013) is a hybrid, combing elements of synthetic models with a detailed model for the stellar envelope.

The first stellar yields from detailed AGB models (Ventura et al. 2001; Herwig 2004) were calculated for a limited ranges of masses and metallicities. Karakas & Lattanzio (2007) published the first extensive grid of stellar yields from detailed AGB models, with an update by Karakas (2010). In these proceedings, we focus on stellar yields published within the last 5 years. Note that many papers provide surface abundances predictions (a few recent examples: Weiss & Ferguson 2009; Campbell et al. 2010; Bisterzo et al. 2010; Kamath et al. 2012; Lugaro et al. 2012; D'Orazi et al. 2013; Cruz et al. 2013) but not tabulated stellar yields.

Stellar yields without *s*-process elements generally focus either on large grids of stellar models covering a significant portion of the mass and metallicity range appropriate for chemical evolution modelling (e.g., Karakas 2010; Ventura et al. 2013, 2014), or difficult areas of the parameter space such as the very low-metallicity regime (Campbell & Lattanzio 2008; Iwamoto 2009; Gil-Pons et al. 2013), super-AGB stars (Gil-Pons et al. 2013; Siess 2010; Doherty et al. 2014a,b), and/or uncertain physics such as mass loss, rotation and/or extra mixing phenomena (Stancliffe & Jeffery 2007; Charbonnel & Lagarde 2010; Lagarde et al. 2011).

Stellar yields that include *s*-process elements are also increasingly becoming available (Cristallo et al. 2009, 2011; Fishlock et al. 2014a; Karakas et al. 2014; Pignatari et al. 2013; Straniero et al. 2014; Shingles et al. 2015). These calculations can be very time consuming so are usually limited in the number of masses and metallicities included. For

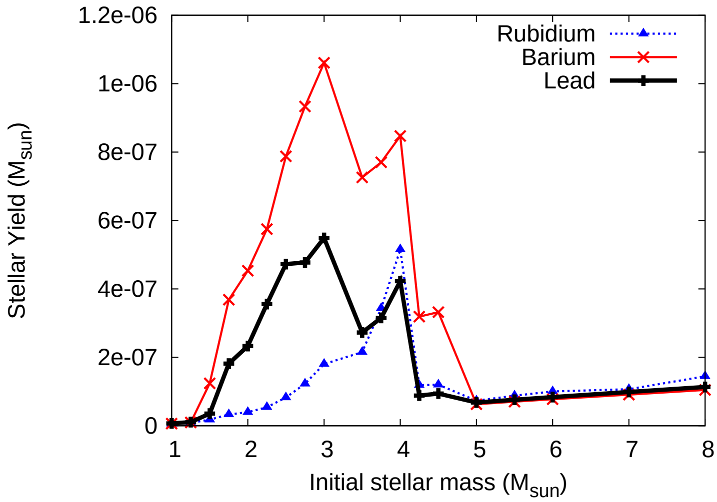

Fig. 3. Stellar yield (in $M_{\odot}$) of Rb, Ba and Pb from the solar metallicity models from Karakas (2014). The yield is the integrated amount of material that is expelled into the interstellar medium over the star's life. Models extend from $1M_{\odot}$, where there is no third dredge-up, to $8M_{\odot}$. Models between $1.5M_{\odot}$ and $4.5M_{\odot}$ have ^{13}C pockets included after each TDU episode (in the same manner as described by Lugaro et al. 2012). Mild HBB begins at $\approx 4.25M_{\odot}$ but is not very efficient until $5M_{\odot}$.

example, there are no yields for *s*-process elements for very low-metallicity AGB models at the present time (although see Campbell et al. 2010; Cruz et al. 2013). To highlight how significant the gap in theoretical *s*-process yields, there currently is not a complete set of *s*-process yields for solar metallicity, covering the full AGB mass range from 0.8–$8M_{\odot}$. An unpublished (Karakas & Lugaro, 2015, in prep) set of yields for Rb, Ba and Pb are shown in Fig. 3[1].

3.1. Uncertainties

The evolution and nucleosynthesis of low and intermediate-mass stars is seriously affected by numerical modelling uncertainties as well as uncertainties in the input physics. We refer to previous reviews on AGB stars for a thorough discussion on this topic (Busso et al. 1999; Herwig 2005; Karakas & Lattanzio 2014).

The main uncertainties include convection and the treatment of convective borders, which influences the efficiency of the TDU and HBB, as well as the formation of ^{13}C pockets in the He-intershell, a necessary ingredient in the synthesis of *s*-process elements in low-mass AGB stars ($M \leq 3M_{\odot}$). Note that we do not know for sure if convective overshoot is the only (or the main) mechanism behind the formation of ^{13}C pockets (we refer to Herwig 2005, for a detailed discussion).

There is observational evidence that suggests that ^{13}C pockets either do not form (or do not produce many free neutrons) in intermediate-mass AGB models (García-Hernández et al. 2013). This idea is supported by theory (Goriely & Siess 2004). There is also conflicting evidence regarding the efficiency of TDU in models with HBB. Observations of Rb enrichments strongly suggests that the TDU occurs in the brightest O-rich AGB stars (García-Hernández et al. 2006; van Raai et al. 2012), whereas Kalirai et al. (2014) suggest

[1] For example, the FRUITY base `http://fruity.oa-teramo.inaf.it/`, recently updated their website to include surface abundances and yields for solar-metallicity models up to $6M_{\odot}$.

that the efficiency of TDU peaks at $\approx 3M_{\odot}$ and decreases in intermediate-mass stars. However, the study by Kalirai et al. (2014) considered a maximum mass of $4.4M_{\odot}$ for their calibration. If low-metallicity AGB stars polluted globular clusters then the TDU cannot have been efficient, as discussed by Fenner et al. (2004).

Mass loss is another major uncertainty affecting AGB models, as it determines the AGB lifetime (Kalirai et al. 2014) and therefore the stellar yields. There have been considerable improvements in observations of mass-losing AGB stars (e.g., Groenewegen et al. 2009; Gullieuszik et al. 2012; Rosenfield et al. 2014, to name a few studies), and in theoretical models of mass loss in AGB stars (see the review by Höfner 2015). However, there is no consensus on how mass loss varies as a function of fundamental stellar parameters for AGB stars across the whole mass range.

Other uncertainties include the input physics (e.g., low temperature opacities, thermonuclear reaction rates, the equation of state, the initial abundances) and the implementation of non-standard physics including magnetic fields, rotation and non-convective mixing processes such as thermohaline (or double-diffusive) mixing. We refer to Karakas & Lattanzio (2014) for a detailed discussion of each of these. We note here that the effect of a binary companion is almost always ignored in calculations of stellar yields (except in synthetic calculations, see Izzard et al. 2006).

4. Conclusions

Significant progress has been made over the past decade in improving our understanding of the AGB phase of stellar evolution. Even so, there are many significant uncertainties that affect the stellar yield calculations, such as mass loss and convection, and these in turn affect the accuracy and reliability of chemical evolution model predictions. Better observations are improving our knowledge of when the third dredge-up turns on for example. We are also slowly improving our understanding of the physics of convection in stellar interiors (e.g., Viallet et al. 2013).

There are also crucial gaps in our knowledge. These gaps are most apparent for AGB stars of very low metallicity (e.g., [Fe/H] ≤ -3) and for the production of elements produced by the *s*-process for all mass and metallicity ranges. Theoretical effort is needed to address these gaps, especially because current and future surveys (e.g., SEGUE, GALAH, APOGEE, and GAIA-ESO) will provide stellar abundances data for hundreds of thousands of stars in our Milky Way Galaxy. Stellar yields from all mass ranges will be needed for the interpretation.

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