Mem. S.A.It. Vol. 88, 237

**Memorie** della

# Cosmic chemistry from AGB stars and its dependence on the initial stellar mass

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**Abstract.** Asymptotic giant branch (AGB) stars synthetise a variety of elements in their deep hot layers, mix them to the stellar surface, and shed them into their surrounding by stellar winds. Through this series of processes (nucleosynthesis, mixing, and winds) they contribute to the chemical evolution of stellar groups and galaxies. Specifically, they significantly produce a number of light elements (such as C an N), as well as roughly half of the cosmic abundances of the elements from Sr to Bi via *slow* neutron captures (the *s* process). This peculiar nucleosynthesis is strictly dependent on the initial stellar mass and the metallicity. In particular, as the stellar mass increases towards the AGB-Supernova transition limit the signature of H burning becomes predominant with respect to that of He burning and neutron captures. We discuss the origin of these differences and their implications on observational constraints from spectroscopic observations of AGB stars and meteoritic stardust.

**Key words.** Stars: abundances – Stars: AGB and post-AGB

## 1. Introduction

Among transitional masses in stellar physics certainly the most fundamental is the mass (~ 7-10 $M_\odot$) discussed in the present conference. From this point in mass the way a star ends its life switches from stellar winds leaving a white dwarf remnant (the AGB regime) to an explosion leaving a neutron star or black hole remnant (the supernova regime). Here we discuss another important mass transition, which is located on the AGB and leads to the AGB-Supernova mass transition: this is the point in mass (~ 3-5 $M_\odot$) where an AGB star turns from C-rich to O-rich (Fig. 1). Different processes characterise the two sides of the transition point: the main feature of the C-rich AGB stars is the third dredge-up (TDU), which brings material from the He- and C-rich intershell to the stellar surface. Because of this mixing process, the abundance of C can overtake that of O, and a C star forms, characterised by C-rich molecules and dust in its envelope. On the other hand, the main feature of O-rich AGB stars in the mass range leading to the AGB-Supernova transition is hot bottom burning (HBB). This occurs when the base of the stellar convective envelope is hot enough for proton captures to be activated producing a clear H-burning signature at the surface of the star. In this process, C is converted into N, and the AGB star remains O-rich, even in the presence of the TDU. Another major feature of the contribution of AGB stars to cosmic chemistry is the presence of free neutrons in their deep layers within the core. These are produced by $\alpha$-capture reactions in the He-rich intershell and lead to the creation of about half the abundances of the elements heavier than Fe. Also in this respect the C-rich and O-rich AGB stars behave differently: the main source of neutrons is the $^{13}$C($\alpha$,n)$^{16}$O reaction in the former case, and the $^{22}$Ne($\alpha$,n)$^{25}$Mg reaction in the latter. In this contribution, we will describe in detail the features of the C-rich/O-rich AGB mass transition, both from the modelling and from the observation point of views. A more detailed review can be found in Karakas & Lattanzio (2014).

## 2. Basics of AGB stars

AGB stars present the typical structure of giant stars with two main components: the extended convective envelope and the compact core. What characterise them more specifically from the observational point of view are their strong pulsations and dusty stellar winds, which can reach extremely high values, up to $10^{-7/-5}$ M$_\odot$/yr. The AGB contribution to cosmic chemistry results from the winds carrying outwards into the surrounding medium elemental abundances freshly produced by nuclear reaction deep in the core of the star, where matter is hot (up to almost 400 MK) and dense (up to $10^4$ gr/cm$^3$), and carried to the stellar surface via convective mixing processes. The core has a very complex structure, which evolves with time in a way unique to AGB stars: there are two burning shells, an H- and an He-burning shell, sitting on top of the C-O degenerate core; between them lays an He-rich "intershell". The two shells are activated recurrently and alternately, the H-burning shell on long timescales ($10^{3-5}$ yr, all timescales decreasing with increasing the stellar mass) and the He-burning shells on short timescales ($10^{2-3}$ yr). Furthermore, each He-burning episode drives a short-lived ($10^{1-2}$ yr) convective region (thermal pulse, TP) over the whole He-rich intershell. Once the TP is extinguished and before H burning resumes, the TDU can occur. Because the timescale of He burning is short, C is produced by the triple-$\alpha$ reaction, while O is not not created as there is not enough time for further $\alpha$-captures on $^{12}$C. As a consequence, the TDU carries C-rich material to the stellar surface and produces a C-rich star, i.e., with C/O>1. In some models (Herwig 2000; Pignatari et al. 2016; Battino et al. 2016) diffusive overshoot is applied at the base of the TPs, and both C and O are carried from the C-O core into the He-rich intershell. In this case a C-rich star can still be produced via TDU, since the C/O ratio in the intershell is still larger than 1, however, also O is enhanced at the stellar surface.

The situation changes at the AGB mass transition point (Fig. 1), where HBB is activated when the base of the envelope reaches temperatures above roughly 60 MK. The temperature required for HBB is much higher than that needed for proton captures in typical core or shell H burning conditions, due to the fact that the density at the base of the envelope is much lower, of the order of 1 gr/cm$^3$ rather than $10^3$ gr/cm$^3$. Due to HBB, C is converted into N via the CN cycle and the star remains O-rich. However, as the temperature increases with the stellar mass and decreasing the metallicity, the full CNO cycle is activated. At equilibrium, the CNO cycle results in almost complete conversion of C and O into N and C/O>1, i.e. a C-rich star. In this specific case, however, it is more appropriate to name the star an N-rich star, since N is the predominant element

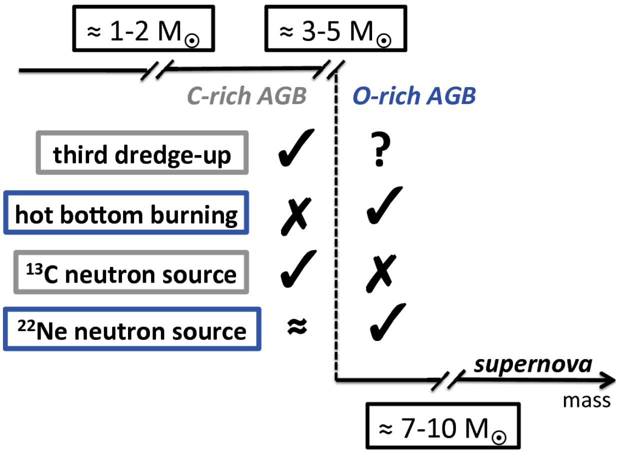

**Fig. 1.** Schematic diagram of the stellar mass transitions mentioned in the text and of the typical processes at work in C-rich and O-rich AGB stars. Note that the O-rich stars discussed here are the massive AGB stars (> 3-5 $M_\odot$) that lead to the AGB-Supernova transition, rather than the lowest-mass AGB stars (< 1.5 $M_\odot$) that do not experience enough TDU to become C-rich.

heavier than H and He at the stellar surface. Furthermore, as the temperature increases, the NeNa and the MgAl cycles are also activated, leaving clear signatures at the surface such as large variation in the Na abundance and in the Mg isotopic ratios, and the production of the short-lived radioactive nucleus $^{26}$Al (with a half life = 0.7 Myr).

Fig. 2 illustrates the transition between C-rich and O-rich AGB stars using the He/H, C/O, and N/O ratios, which are those most affected by the activation of HBB. It also illustrates how the value of the mass transition cannot be exactly defined, and how models implementing different mixing schemes for convection produce different results. The first evidence of the transition mass was presented by Wood et al. (1983), who observed that in the LMC and SMC all the AGB stars more luminous than $M_{\rm bol} \sim -6$ are non-carbon stars. For those metallicities this limit corresponds to masses around 4 $M_\odot$ (D'Antona & Mazzitelli 1996), depending on the details of the models. The situation has not changed drastically in the past decades, for example, based on SAGE observations of the LMC, Woods et al. (2011) concluded that C-rich AGB stars have $\sim -5$, while O-rich AGB stars have two peaks, one at lower and one at higher magnitude, with the one at higher magnitude possibly due to O-stars currently undergoing HBB. Further indirect observations of the occurrence of HBB come from the C, N, and O ratios observed in planetary nebulae. For example, considering a sample of planetary nebulae in the LMC Ventura et al. (2015) recently concluded that HBB is required to interpret the nitrogen-enriched planetary nebulae. Finally, isotopic ratios, when available, represent a strong indication of HBB. For example, the $^{18}$O(p,$\alpha$)$^{15}$N reaction destroys $^{18}$O very quickly and efficiently during H-burning. Justtanont et al. (2015) recently reported the detection of the $^{16}$O and $^{17}$O isotopologues of water in O-rich AGB stars compatible with being of relatively high mass, however, the lines due to $H_2{}^{18}O$ are absent, in agreement with HBB.

Another crucial question is if the TDU occurs in the massive O-rich AGB stars. The occurrence of TDU is strongly model dependent, specifically, it depends on the amount of overshoot applied at the base of the convective envelope, and even more as the stellar mass increases. While the answer to this question is debated, its implications are considerable. In fact, the TDU provides extra fuel

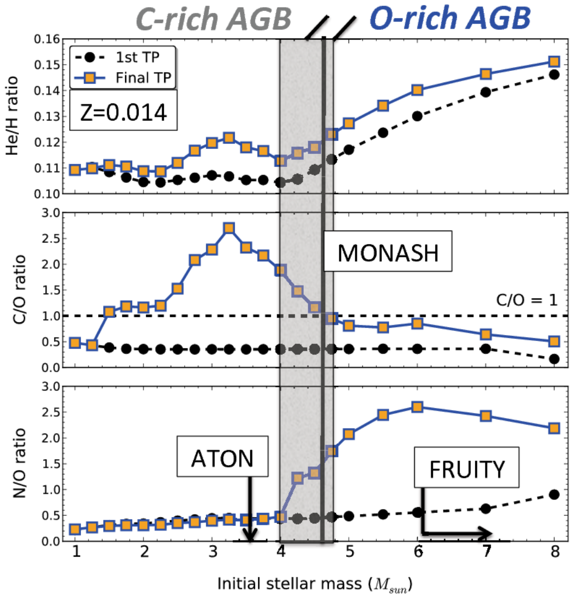

**Fig. 2.** Selected elemental ratios at the stellar surface of AGB stars at the end of the computed evolution as function of the initial mass from the MONASH models of solar metallicity presented by Karakas & Lugaro (2016). If the mass transition from C-rich to O-rich AGB stars is set at the point where C/O becomes lower than unity, in these models this corresponds to 4.6 $M_\odot$. However, the effect of HBB are already visible in the increase in He and N abundances at masses below that where the conversion to C/O<1 occurs, and considering a transition region is more appropriate (grey shaded area starting from 4 $M_\odot$). Note that for the ATON models (based on the description of Mazzitelli et al. 1999) the transition mass is at 3.5 $M_\odot$, due to the implementation of a more efficient treatment of convection (the full spectrum of turbulence, FST). On the other hand, FRUITY models (Cristallo et al. 2015) computed up to 6 $M_\odot$ do not experience HBB at solar metallicity, possibly due to the different mixing algorithm. (Figure adapted from Fig. 2 of Karakas & Lugaro 2016).

for HBB resulting in a significant increase of the yields of some key isotopes: e.g., more $^{12}$C from TDU results in more $^{14}$N, more $^{22}$Ne results in more $^{23}$Na (see, e.g., the recent work by Slemer et al. 2017), and more $^{25}$Mg results in more $^{26}$Al. Again, the different models predict different TDU efficiencies: the MONASH models have relatively large amount of TDU mass, the FRUITY models extremely small, while the results for the ATON models vary, depending on the explicit inclusion of an extra-mixing parameter. The second important effect of the presence of the TDU is to carry the products of *slow* neutron captures (the *s* process discussed in the next section) from the intershell into the envelope. If the TDU is present, the abundances of some key elements heavier than Fe can be enhanced at the stellar surface of O-rich massive AGB stars.

## 3. The neutron sources and the *s* process

The *s* process is well known to occur in C-rich AGB stars. Direct evidence for it was already discovered in the 1950s thanks to observations of overabundances of the elements heavier than Fe such as Sr, Y, Zr, Ba, Nd, Sm, and even of the presence of Tc (Merrill 1952), a radioactive element that needs to be produced *in situ* to be observed in a giant star before it decays within less than a million years. To explain these observations free neutrons are needed to drive the *s* process. The best candidate neutron source

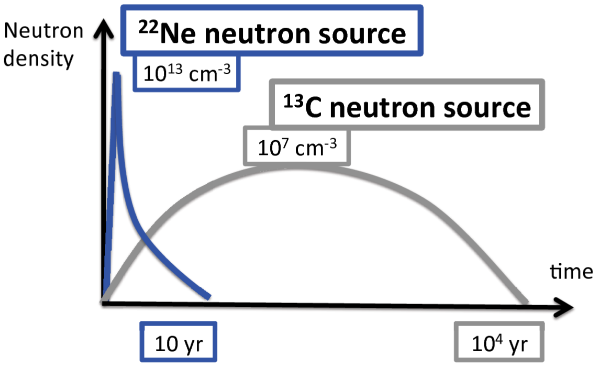

**Fig. 3.** Schematic diagram showing the typical profile of the neutron density versus time in the case of the $^{13}$C and of the $^{22}$Ne neutron sources. Orders of magnitude timescales and peak neutron density are indicated. The integrated area below the curves is a proxy for the total number of free neutrons.

in C-rich AGB stars is the $^{13}$C($\alpha$,n)$^{16}$O reaction because it is activated already at low temperatures, around 90 MK. To produce enough $^{13}$C some mixing of protons from the envelope into the $^{12}$C-rich intershell is assumed to occur in the models at the deepest extent of each TDU episode. The $^{12}$C(p,$\gamma$)$^{13}$N($\beta^+$)$^{13}$C reaction chain results in the production of $^{13}$C within a so-called $^{13}$C *pocket*. The $^{13}$C burns typically during the periods in-between TPs and releases a large amount of free neutrons over a long timescale (see Fig. 3). This results in a strong production of elements heavier than Fe in the pocket (by up 4-5 orders of magnitude relatively to their initial abundances), which are subsequently mixed with the whole intershell during the following TP, and carried to the stellar surface by the TDU.

On the other hand, the $^{22}$Ne($\alpha$,n)$^{25}$Mg reaction is activated only when the temperature reaches above roughly 300 MK, i.e., inside the TP of the O-rich massive AGB stars (and only marginally for masses $\sim$ 3 M$_\odot$). The $^{22}$Ne is abundant in the intershell as the result of double $\alpha$-captures on the main product of the previous H burning $^{14}$N. The features of the neutron flux released by the $^{22}$Ne neutron source are opposite to those of the $^{13}$C neutron source (fig. 3). The timescale is much shorter, thus the total number of free neutrons released are much smaller. On the other hand, the neutron density can reach peak values that are orders of magnitudes higher than in the $^{13}$C pocket, activating *branching points* on the *s*-process path.

In particular, the high neutron densities (above roughly $10^{10}$ cm$^{-3}$) required to activate the branching point at the unstable $^{86}$Rb (half life of 19 days) are reached. This results in a timescale for neutron captures on $^{86}$Rb faster than the timescale for $\beta^-$ decay, leading to the production of the $^{87}$Rb nucleus, which has a magic number of neutrons equal 50 and thus a low neutron-capture cross section. The abundance of $^{87}$Rb accumulates producing higher than solar Rb/Zr ratios (where Zr is a neighbouring *s*-process element). This is in sharp contrast to C-rich AGB stars where the $^{13}$C is the neutron source, the neutron densities are not high enough to activate the branching point at $^{86}$Rb, and the Rb/Zr ratios are lower than solar instead, as observed in C-stars (Abia et al. 2001). First evidence of this enhanced Rb production resulting from the activation of the $^{22}$Ne neutron source in O-rich massive AGB stars was discovered by García-Hernández et al. (2006, 2009) and recently revised by Zamora et al. (2014); Perez-Mesa et al. (2017).

While qualitative agreement is found between models and observation, some issues are still open both from the observational and theoretical point of views (van Raai et al. 2012; Karakas et al. 2012; Perez-Mesa et al. 2017). Interestingly, Rb has recently also been observed in planetary nebulae (Sterling et al. 2016). Such new constraints will provide the opportunity to confirm the connection between Rb production and HBB as well as clarify the details of the activation of the neutron source in massive AGB stars. Finally, the non-detection of the short-lived element Tc in massive O-rich AGB stars (García-Hernández et al. 2013) is in agreement with model predictions when the $^{22}$Ne neutron source dominates and the $^{13}$C pocket is not present. In fact, theoretical models for the formation of the $^{13}$C pocket (Goriely & Siess 2004; Cristallo et al. 2015) predict that the $^{13}$C pocket should be inefficient in these stars.

## 4. Stardust grains

Stardust grains recovered from primitive meteorites condensed in the expanding atmospheres of stars and in supernova and nova ejecta and the vast majority of them come from AGB stars. A puzzling discrepancy has so far been observed in that a significant contribution to the presolar nebula oxide/silicate stardust inventory is predicted from O-rich massive AGB stars (Gail et al. 2009; Zhukovska et al. 2015), however, no such dust with the signature of HBB had ever been found in meteorites. Some grains have $^{18}$O/$^{16}$O ratio orders of magnitude lower than solar (the oxide and silicate stardust "Group II" grains), as predicted by HBB and observed by Justtanont et al. (2015), who derived $^{18}$O/$^{17}$O<0.1. However, the predicted $^{17}$O/$^{16}$O ratio is roughly a factor of two higher than measured in the grains (Lugaro et al. 2007; Iliadis et al. 2008).

This problem was solved by a new experiment performed at the Laboratory for Underground Nuclear Astrophysics (LUNA) in the National Laboratory of Gran Sasso (LNGS, Italy)[1]. Three years of underground measurement of the $^{17}$O(p,$\alpha$)$^{14}$N reaction revealed that its rate is roughly twice higher than estimated before (Iliadis et al. 2010) at the temperature of HBB (Bruno et al. 2016). This results in a $^{17}$O/$^{16}$O ratio produced by HBB two times lower than before, in agreement with the stardust Group II data (Lugaro et al. 2017). Also Mg and Al isotopic ratios can be measured in these grains, and can be used in the future to provide stringent constraints for O-rich massive AGB models, for which observations are still relatively sparse.

Future plans of LUNA involve the installation of a new accelerator LUNA-MV(MegaVolt) including a beam of carbon. A few years (up to 5) of measurements will reveal the most accurate value to date for the rate of the $^{12}$C+$^{12}$C reaction, which is crucial for the AGB-Supernova mass transition, as it controls the temperature of C-burning with strong feedback on the stellar structure.

*Acknowledgements.* ML is a Momentum ("Lendület-2014" Programme) project leader of the Hungarian Academy of Sciences. This work is supported by the Hungarian OTKA research funding scheme, project K120666. DAGH acknowledges support provided by the Spanish Ministry of Economy and Competitiveness (MINECO) under grant AYA-2014-58082-P. DAGH was also funded by the Ramón y Cajal fellowship number RYC-2013-14182.

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