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Nucleosynthesis in AGB Stars

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Abstract. I review some of the main nucleosynthesis processes in Asymptotic Giant Branch (AGB) Stars. These include production of ^{12}C, ^{19}F, ^{22}Ne and *s*-elements in the He-rich layers above the degenerate C-O core, and modifications in the abundances of intermediate-mass elements up to Mg-Al, due to proton captures above the H-burning shell. Emphasis is put on the uncertainties still affecting the yields (especially mixing processes and mass loss rates) and on the possible role of planetary nebulae as a source of information on the evolution and nucleosynthesis of the AGB progenitors

Keywords. Stars: evolution; Stars: AGB and Post-AGB; Stars: mass loss; Nuclear reactions, nucleosynthesis, abundances.

1. Introduction

Considering the topics discussed in this symposium, in this short review I shall concentrate on nucleosythesis phenomena in Asymptotic Giant Branch (AGB) stars of interest for observations in Planetary Nebulae (PNe) and I shall not enter into evolutionary details; for them, the reader can find a presentation by Falk Herwig in this same book.

From the point of view of element production, AGB stars are well known as the main site where the *s*-process occurs, i.e. where the slow addition of neutrons proceeding along the valley of β-stability generates about 50% of nuclei beyond the Fe-peak. For a recent review see Busso *et al.* (2004). There are however a number of other elements and isotopes for which AGB stars are important manufacturing sites. We can broadly divide them into two groups: the H-burning products (mainly coming from regions across and above the H-burning layers) and He-burning products (mainly coming from He-rich zones, above the degenerate C-O core). Several such nuclei of both groups might be suitable for direct observational tests in PNe, so that below I shall briefly discuss the two major AGB nucleosynthesis sites, mentioning possible consequences for PN abundances.

Preliminarily, a word of caution is mandatory. As we shall see, production of the *s*-elements and of most intermediate-mass isotopes still depends on uncertain parameters. These parameters concern stellar mixing phenomena (both convective, i.e. the extension of dredge-up, and diffusive). Secondly, the same total amount of envelope mass that can be polluted by newly synthesized materials is a function of the mass loss history. Too strong mass loss rates, preventing a star from passing through at least a few thermal pulses before ejecting the planetary nebula, would strongly limit the expected evidence of chemical peculiarities in the PN itself. The knowledge of mass loss (and luminosity) of AGB stars is very poor and only now it is starting to become quantitative, thanks to the availability of large sets of mid-far infrared (IR) data from space missions like ISO, MSX and Spitzer. As an example, figure 1 shows how known mass loss rates (measured at radio wavelengths) can now be correlated to IR colors, with the aim of deriving trends that can then be applied to sources with unknown mass loss (see Guandalini *et al.* 2006 for details). Despite the use of space-based observations and of the best available mass loss rates and distances, the relation still gives poor constraints.

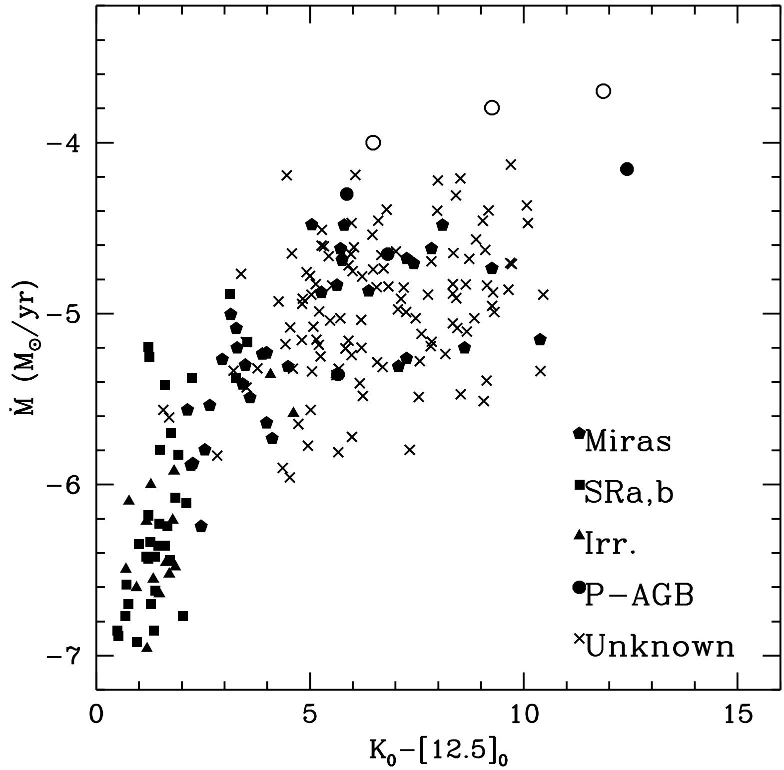

Figure 1. Mass loss rates of various classes of AGB stars, as a function of the infrared color K-[12.5] computed from ISO and MSX data. The relation is not linear and still rather disperse.

2. Nucleosynthesis and Mixing in the He-rich layers

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The main neutron source is recognized to be the ^{13}C(α, n)^{16}O reaction, whose activation however depends on still unknown mixing mechanisms that must inject hydrogen from the envelope into the He-rich region, during the third dredge-up phenomenon. Here it reacts on the abundant ^{12}C, producing ^{13}C. Stellar model calculations (see e.g. Straniero *et al.* 1997, Gallino *et al.* 1988) showed that any ^{13}C produced in the radiative He-rich layers at dredge-up burns locally before a convective pulse develops. The temperature is rather low for He-burning conditions [$(0.8 - 0.9) \times 10^8$ K], and the average neutron density never exceeds 1×10^7 n cm^{-3}. As a consequence of neutron captures, a pocket of *s*-enhanced material is formed and subsequently engulfed into the next pulse. Here *s*-elements are mixed over the whole He intershell by convection and are slightly modified by the marginal activation of the ^{22}Ne source. They are then brought to the surface during the following episode of dredge-up from the envelope (this is the so-called *third* dredge-up, which is however a repetition of a few to many individual episodes, one after each He-shell instability). Such a scheme, illustrated in figure 2, has been confirmed by all recent computations (Goriely & Siess 2001; Lugaro *et al.* 2003).

Various physical mechanisms have been proposed to solve the problem of proton ingestion (see Herwig 2005; Herwig *et al.* 2003). None of them, however, is exempt from free parameterizations, so that the amount of ^{13}C burnt has usually been assumed as a free

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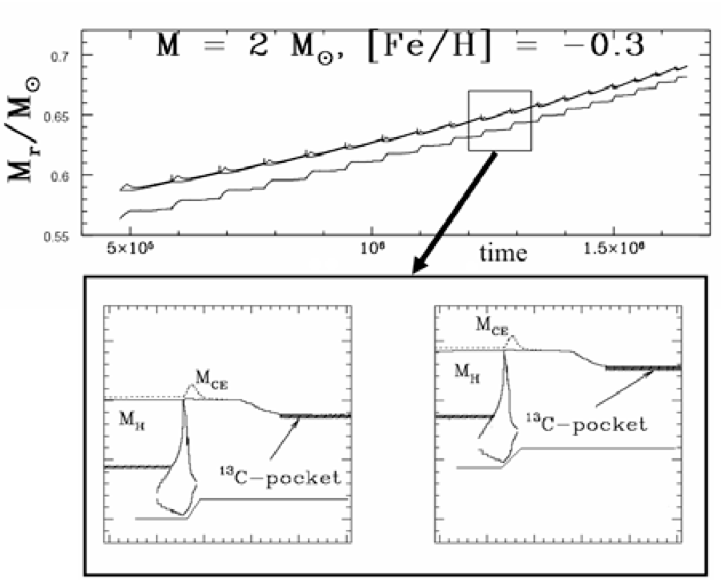

Figure 2. The top panel shows the position in mass of the He-shell, the H-shell and the base of the convective envelope in an AGB star undergoing thermal pulses. The marked zone is enlarged in the bottom panel, which shows the layers relevant to *s*-processing, across two successive pulses.

parameter, to be calibrated by observations. Luckily, *s*-processing affects a large number of observable elements, and depends only on a few basic quantities (the neutron density, the total neutron flux, the very small cross sections of key nuclei, having *magic* neutron numbers, i.e. closing nuclear shells), so that observational constrains are very effective. Moreover, the recent advent of precise isotopic measurements on pre-solar grains formed in AGB circumstellar environments helps in specifying the local conditions very well (Gallino *et al.* 1997, Amari *et al.* 2001). Despite the embarrassing problems affecting the neutron source, we can therefore say that neutron captures in AGB stars are among the best known nuclear processes in astrophysics. We see that a large spread exists at any metallicity in the amount of ^{13}C produced, probably reflecting differences in the triggering mechanisms as a function of the stellar mass (Busso *et al.* 2001), but we also know that a sort of universal average is required, at any [Fe/H] value, if we want to reproduce the chemical evolution of *s*-process nuclei, yielding about 4×10^{-6} $M_\odot$ of ^{13}C per each pulse-interpulse cycle. This value has been often indicated as the *standard* (ST) one.

The ^{13}C neutron source, as operating in AGB models, is of “primary” origin, i.e. derives from processes starting directly from the original H of the star. One of the major consequences of this fact is that the ensuing *s*-process distribution is extremely dependent on the initial abundance of Fe-group seeds, i.e. on stellar metallicity. Indeed, the neutron exposure τ is roughly proportional to the number of available ^{13}C nuclei per Fe seed, hence inversely proportional to the metallicity. Then, in the galactic disc, the neutron exposure tends to be larger in AGB stars of lower [Fe/H]. This has important effects on *s*-process abundances, as shown in figure 3. The figure uses a common notation, in which the average abundances of various elements at the Ba-peak are collectively indicated by the symbol *hs* (heavy s-elements). In this case *hs* includes Ba, La, Nd.

Assuming as a guidance the mentioned average ^{13}C abundance per pulse-interpulse cycle, the neutron exposure available at solar metallicity would produce mainly *s*-elements

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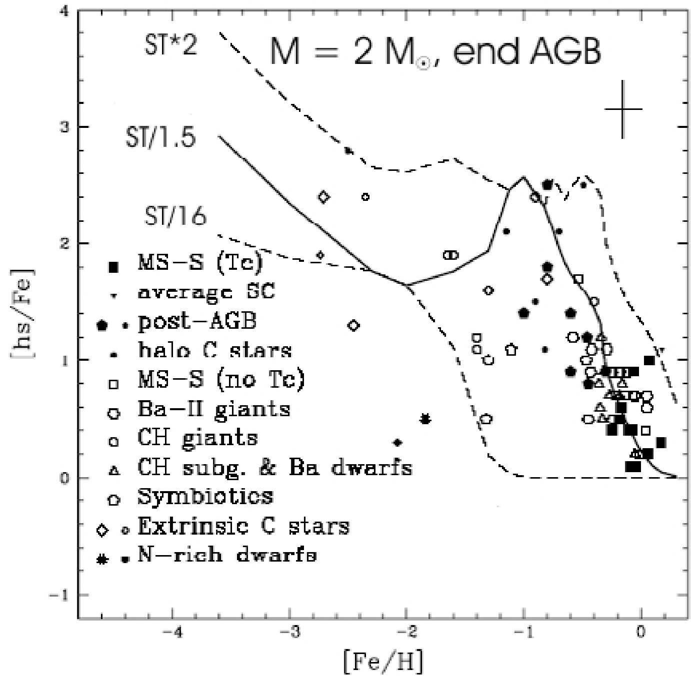

Figure 3. Model predictions and observations in AGB stars for the collective abundances of *s*-elements at the Ba-peak (hs) as a function of metallicity. Model curves are computed for choices of the ^{13}C amount equal to the ST one mentioned, multiplied by 2, 2/3, and 1/16, roughly representing the whole possible spread.

at the Sr-Y-Zr peak (neutron magic number N = 50) and this should be seen *on average* in metal-rich PNe. For decreasing [Fe/H], one has more neutrons available per Fe seed, the N = 50 bottleneck is bypassed, and the higher-mass nuclei up to Ba-La-Ce-Pr-Nd are produced, with a maximum at $Z \approx Z_{\odot}/4$ (Travaglio *et al.* 1999). For even lower metallicity, one would have enough neutrons per Fe seed to feed Pb, in particular the abundant isotope ^{208}Pb at the magic neutron number N = 126. (Travaglio *et al.* 2001). Eventually, below [Fe/H] = −1, though all the initial Fe is efficiently converted to heavy *s*-elements and to Pb, so that the abundances of neutron-rich elements *relative to iron* continue to increase (see figure 3), the shortage of iron seeds becomes dominant, so that the *absolute* production of all *s*-elements, including Pb, decreases with metallicity. Due to this fact, and to the long lifetime of stars ending their evolution on the AGB, which allows them to contribute only late to the chemical evolution of the interstellar medium, *s*-process abundances in the Galaxy are expected to decrease and eventually to vanish at very low values of [Fe/H], where the neutron-rich elements must be dominated by the *r*-process (see, e.g., Simmerer *et al.* 2003, and references therein). The combined results of the above trend and of the spread of ^{13}C abundances at each [Fe/H] value imply a wide spectrum of different abundance distributions in AGB stars of spectral types MS-S-SC and C, i.e. those normally seen to be enriched in *s*-elements. In general, however, each distribution can be rather precisely modelled with a suitable choice of the ^{13}C abundance.

In several cases, chemically peculiar stars of the mentioned MS-S-SC-C sequence have been shown to belong to binary systems, and the same *s*-element enrichment is often the result not of a direct nucleosynthesis phenomenon on the same star we see now, but rather of a mass transfer episode from an AGB companion evolved previously. These cases can be discriminated observationally by the absence of Tc in the spectra. Indeed, the unstable ^{99}Tc ($t_{1/2} = 2 \times 10^5$ yr), first seen on AGB stars by Merrill (1952), lies on the main *s*-process path, and is therefore expected to be produced copiously. Its lifetime is longer than any inter-pulse phase, so that in a normal AGB star it should be present in the photosphere. If, however, we are looking at a binary system in which *s*-enriched material was transferred a long time ago, Tc must be absent in the spectrum. Conversely, the decay of ^{93}Zr ($t_{1/2} = 1.56 \times 10^6$ yr) should at that point have produced ^{93}Nb. We have therefore a double check: in single, bona-fide TP-AGB stars Tc must be present and Nb absent (its original abundance is destroyed by n-captures, and it is not significantly produced by the *s*-process directly), while in binary stars polluted by an AGB companion the reverse must be true. PNe descending from the two classes of progenitors (single or binary) should show the same evidence in terms of Tc and Nb as the progenitor itself did, as the formation of a PN is too short in time to significantly affect the presence/absence of the two isotopes.

In the same environment where the *s*-elements are produced, the abundances of various intermediate-mass nuclei are partly or largely modified, First of all, ^{12}C is formed and dredged-up: in a range of masses from around 1.7 to about 4 $M_\odot$ this process is efficient enough to let the whole envelope become carbon rich, forming a C(N) star (Abia *et al.* 2001, Abia et al 2002). Below this interval, dredge-up is not efficient enough to increase the C/O ratio above unity, at least for solar metallicity (Busso *et al.* 2001); above it, occurrence of hot bottom burning (hbb: Karakas & Lattanzio 2004), i.e. of hydrogen burning directly at the bottom of the convective envelope, should consume most carbon dredged-up, so that a C star is not formed. All C-rich PNe should therefore descend from progenitors in the mentioned mass interval ($1.7 - 4\ M_\odot$).

Another important feature expected in PN abundances, as a consequence of AGB nucleosynthesis, is the enrichment in ^{22}Ne. This isotope derives from two α-captures on the abundant ^{14}N, so that it grows to very high abundances in the He-layers. Since we now recognize that ^{22}Ne is only marginally burnt in most AGB stars (at least below 5 $M_\odot$), a considerable portion of it should be dredged up and be seen in the subsequently-formed PN. Here ^{22}Ne might dominate over ^{20}Ne, so that PNe might be the origin of the known materials transporting this chemical anomaly (Ne-E) to the solar system (Gallino *et al.* 1990). Any Ne-enhancement seen in PNe has to be ascribed to ^{22}Ne.

Finally, again starting from the abundant N left by H-shell burning, a couple of captures (a neutron first, then an α-particle) lead to ^{19}F, which in fact is observed in AGB stars, and correlated with *s*-elements and carbon: see Renda *et al.* (2005).

3. Nucleosynthesis and Mixing in the H-rich Layers

Observations of evolved stars below $\sim 2\ M_\odot$ reveal an isotopic mix of intermediate-mass elements that cannot be accounted for by convective dredge-up: see e.g. Straniero *et al.* (1997). Such chemical anomalies are found above the so-called *luminosity bump* of the red giant branch. The problem has emerged from data accumulated since the early nineties, for various elements between lithium and oxygen (Gilroy & Brown 1991, Pilachowski *et al.* 1991, Gratton *et al.* 2000). Higher mass elements up to Mg show peculiarities and anti-correlations already on the Main Sequence in low mass stars of Globular Clusters (Gratton *et al.* 2001): they might be related to mixing phenomena

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occurring in previous generations of red giants. Excellent reviews of these phenomena can be found in the literature, e.g. Kraft (1994), Charbonnel (2004).

Non-convective circulation of material exposed to partial H burning is usually assumed to explain the above anomalies (Herwig 2005). Partial p-captures in these circulating material are often called cool bottom processes (hereafter cbp). Mechanisms invoked to account for the required cbp include shear instabilities and the meridional circulation induced by rotation (Zahn 1992, Denissenkov *et al.* 1998). Most models consider the chemical mixing through some diffusion-like treatment, leaving the values of the diffusion coefficient and of the mass mixed as free parameters, see e.g. Denissenkov & Tout (2000). In fact, in low mass red giants the internal structure leads us to envisage quite naturally the existence of a shear layer, at the contact between the almost rigid rotation of the stellar radiative core, and the differentially rotating convective envelope. Very recently, however, the idea of a purely rotationally-induced mixing has undergone strong difficulties (Palacios *et al.* 2003, Goriely & Siess 2004), and has been integrated by considering magnetic field buoyancy below the convective envelope (Busso *et al.* 2006).

Whatever the mechanism is that drives cbp, Nollett *et al.* (2003) showed that it can be approximated by a circulation occurring at a rate $\dot{M}$, and reaching down to a maximum temperature T_P, close to, but lower than, the H-burning shell temperature. In this simple scheme it was easy to show that a number of abundance anomalies observed in presolar oxide grains of AGB origin could be explained. This includes destruction, in the stellar envelope, of ^{18}O, production of ^{17}O (sometimes close to CNO equilibrium), and production of ^{26}Al. Any such circulation should also decrease the ^{12}C/^{13}C ratio, and increase the abundance of ^{14}N, in a percentage that is mainly a function of the circulation rate (while Al production is essentially only a function of the temperature T_P reached).

All the above abundance changes expected in low mass AGB stars can be ascribed to admixtures of envelope material and partially CNO-cycled matter originally laying above the H shell, and carried to the surface by rotational or magnetic mixing mechanisms. It should therefore be easily understood that the abundance variations introduced, in more massive stars, by the already mentioned hot CNO cycling directly in the envelope (hbb) are qualitatively of the same nature, only quantitatively more effective. It was shown (Wasserburg *et al.* 2006) that cbp can yield ^{26}Al/^{27}Al envelope ratios of the order of 0.01; hbb at its extreme level can bring this ratio to unity (Karakas 2003). It was also shown (Nollett *et al.* 2003) that cbp can delay the formation of a C-star by burning some ^{12}C; it is expected that hbb prevents the formation of a C star completely, apart from some special and rare cases (Frost et al 1998). Hence it might be not so simple, from PN observations of intermediate elements alone, to understand which kind of progenitor mass was involved. A more stringent constraint might come from Mg isotopes: in massive ($M \geqslant 5\ M_{\odot}$) AGB stars more efficient burning of ^{22}Ne in the He-layers produces ^{25}Mg and ^{26}Mg. The first one might be partly affected, in hbb conditions, by p-captures producing ^{26}Al; but the second should remain as a clear test. Remarkable enhancements of ^{26}Mg should occur only for rather massive AGB progenitors.

4. Conclusions

I have briefly reviewed the present status of AGB nucleosynthesis studies, underlying a number of characteristic features in the distribution of elements and isotopes produced, warning that the predictions still depend on uncertain parameters of the final AGB stages, especially mixing mechanisms and mass loss. In any case, for a practical use, the main expectations for PN abundance patterns descending from the modelling of nucleosynthesis in their progenitors can be summarized as follows.

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• An enrichment in *s*-elements, whose distribution in mass would be informative of the amount of ^{13}C burnt and/or of the metallicity of the progenitor. Independent measurements of this last parameter (e.g. through elements not affected by AGB nucleosynthesis) would disentangle the effects of the two parameters.

• An enrichment in Tc, or alternatively in Nb: the first case occurs for a single AGB progenitor, the second for a binary progenitor in which *s*-elements were added by a mass transfer (e.g. if the secondary companion that receives the transfer has a mass too small to produce and/or dredge-up an *s*-element enrichment of its own).

• An enhanced Ne abundance, dominated by ^{22}Ne from the He-shell; and a measurable enrichment in fluorine.

• Isotopic and elemental mixes of intermediate elements indicative of H-burning (enhancement of ^{13}C, ^{14}N, ^{17}O, destruction of ^{18}O, presence of ^{26}Al). This evidence should be mild for low mass progenitors with cbp, strong for higher mass progenitors with hbb

• Possibly, an anomalous Mg isotopic mix, especially if the progenitor was massive enough to trigger ^{22}Ne burning efficiently.

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