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s-Processing in AGB Stars and the Composition of Carbon Stars

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Abstract

We briefly review the researches on *s*-process nucleosynthesis, starting from the original studies where the phenomenological approach based on solar system abundances was founded, and summarizing the improvements that subsequently led to a crisis in the traditional ideas and to a new scenario in which reliable distributions of nuclei synthesized by slow neutron captures can be provided directly (and solely) by stellar models. In analyzing these last, we concentrate on recent work for low- and intermediate-mass stars in their final evolutionary stages, when they climb for the second time along the red giant branch. We summarize our knowledge of their evolution, mixing, and neutron capture nucleosynthesis, and we discuss some of the many open problems. In particular, we underline the fact that modeling the formation of the main neutron source still requires rather free parameterizations. The results of *s*-process calculations are then illustrated and compared with spectroscopic observations at different metallicities, with special attention to carbon stars.

1.1 Introduction

Not many years after the 50th anniversary of the Carnegie Institution, the first fundamental paper on stellar nucleosynthesis appeared. Presented by Burbidge, Burbidge, Fowler, & Hoyle (1957; hereafter B^{2}FH), it laid the general scenario of nuclear processes in stars, inferring their effects for the production of nuclei and the ensuing evolution of matter in galaxies. Concerning the specific problem of neutron captures for the synthesis of heavy elements beyond Fe, of comparable importance were the compilation of meteorite abundances by Suess & Urey (1956) and the works by Greenstein (1954) and by Cameron (1954, 1957) on the neutron sources that must be activated. Following B^{2}FH, neutron-addition reactions have since been divided according to their slow (*s*-process) or rapid (*r*-process) time scales, as compared to those of β-decays from unstable nuclei encountered along the neutron capture path. Many improvements on the first ideas by B^{2}FH were soon presented, thanks to increased precision in the measurements of isotope abundances from meteorites (Goldberg, Muller, & Aller 1960) and of neutron capture cross sections (Macklin & Gibbons 1965). Various reviews dealing with the *s*-process and with connected stellar and nuclear issues have been published over the years. For a general outline of the stellar environment and its physics, we mention those by Iben & Renzini (1983), Iben (1991), Sackmann & Boothroyd (1991), and Wallerstein et al. (1997). Emphasis on the nucleosynthesis processes is given in Wheeler, Sneden, & Truran (1989), Meyer (1994), Gallino, Busso, & Lugaro (1997), and Busso, Gallino, & Wasserburg (1999).

The above summaries deal with the studies on stellar neutron captures in different moments of their development, and testify to an evolution in which the role of verifying the theory has gradually moved from solar system abundances to stellar spectroscopy, especially for the asymptotic giant branch (AGB) stars where neutron-rich elements are produced in the inner regions and then carried to the surface by a series of mixing phenomena known under the name of *third dredge-up* (hereafter TDU; Smith & Lambert 1990; Luck & Bond 1991; Vanture 1992). Modern upgrades of these studies have included an analysis of abundances in evolved stars of very different metallicity (Busso et al. 2001), in C-rich stars of types SC, C(N), and in post-AGB stars (Abia & Wallerstein 1998; Van Winckel & Reyniers 2000; Abia et al. 2001, 2002; see also Reyniers & Van Winckel 2004). Another source of constraints emerged when solid condensates of presolar origin began to be recovered from meteorites, many of which were ascribed to AGB star envelopes (see, e.g., Anders & Zinner 1993; Ott 1993; Zinner 1997). The high precision reached in the measurements of the isotopic composition of such grains made them an increasingly important source of data for fixing the details of the s-process distribution (Käppeler 2001).

In this paper we review these topics, from a summary of the classical analysis of slow neutron captures (§1.2) to the discovery of growing problems (§1.3), which ultimately led to a new generation of models. Then we present the updated view of low- and intermediate-mass star evolution provided by such models, especially for the final phases where the bulk of slow neutron captures occur (§1.4), and a comparison of model results with observational constraints at different metallicities (§1.5). In particular, a detailed analysis is given of the present understanding of carbon-rich and s-process-rich stars in the Galaxy (§1.6).

1.2 The Classical Analysis of the s-Process

A lucky circumstance favored since the beginning the understanding of the s-process: the distribution is controlled by a small number of parameters and can be approximated analytically. The mathematical tools were presented by Clayton et al. (1961) and by Seeger, Fowler, & Clayton (1965), who outlined the so-called *phenomenological approach* or *classical analysis*. These authors compared the experimental distribution of $\sigma N_{s,\odot}$ products (s-process fraction of the abundance of each nucleus times its neutron capture cross section) with a model σN_s curve, by computing analytically the s-process contributions N_s to each isotope. As a consequence, the ratio $(N_i^{\odot} - N_s)/N_i^{\odot}$ yielded a prediction on the more complex r-process distribution. Studies on the s-process were then shown to provide a rather deep and thorough view of heavy isotope nucleosynthesis.

Many interesting properties of slow neutron captures derive directly from the basic equations of the process. If two nuclei of atomic mass number $A-1$ and A undergo only neutron captures (i.e. the reaction chain is for them *unbranched*), then the abundance $N(A)$ varies in time as

$$\frac{dN(A)}{dt} = N(A-1)n_n\langle\sigma_{A-1}\upsilon\rangle - N(A)n_n\langle\sigma_A\upsilon\rangle, \tag{1.1}$$

where $\langle\sigma\upsilon\rangle$ indicates the Maxwellian-averaged product of cross section and relative velocity, and n_n is the neutron density. By replacing time with the time-integrated neutron flux, or *neutron exposure* τ, through the substitution

$$\tau = \int \Phi_n dt = \int n_n \upsilon_T dt, \tag{1.2}$$

(here υ_T is the thermal velocity), and indicating by $\bar{\sigma}$ the ratio $\langle \sigma \upsilon \rangle / \upsilon_T$, one has

$$\frac{dN(A)}{d\tau} = N(A-1)\bar{\sigma}(A-1) - N(A)\bar{\sigma}(A). \tag{1.3}$$

This relation, in steady-state conditions, yields $\bar{\sigma}(A)N(A)$ = constant, a rule that is rather well satisfied over large intervals of atomic mass number in the experimental σN_s curve of solar system material. The smoothness of the distribution was found to be interrupted by steep drops at nuclei with closed neutron shells, for neutron numbers N = 50, 82, and 126 (the so-called *magic* neutron numbers). For elements produced mainly by the *s*-process, this happens close to mass numbers A = 88, 138, and 208, where neutron capture cross sections become very small (a few millibarns, i.e. a few $\times$ 10^{-27} cm^2); solar abundances show correspondingly remarkable peaks for these atomic mass numbers (Anders & Grevesse 1989).

From inspection of the solar σN_s curve, two main conclusions were derived already in the early analyses. The first was that the *s*-process could not be unique. A series of different physical mechanisms, occurring in separated astrophysical environments, had to provide a multiplicity of τ values in order to bypass the bottlenecks introduced in the neutron capture path by the small cross sections of neutron magic nuclei. One of the components of the process had to account for the *s* nuclei of $A \leq 88$ (the *weak s*-component), and a second one was necessary for nuclei with $88 \leq A \leq 208$ (the *main* component). A third (*strong*) component was also assumed for producing roughly 50% of ^{208}Pb, which apparently could not be explained in other ways (Clayton & Rassbach 1967). The other remarkable conclusion was that, in order to simulate analytically the effects of the above different processes, one could assume either a limited number of intense fluxes or a continuous distribution of decreasing neutron exposures (in which many nuclei could capture a small number of neutrons, and only few nuclei could capture a large number of them): see Seeger et al. (1965) and Clayton (1968). This second alternative soon became very popular, as it was easily approximated by a power law or by an exponential distribution of neutron exposures, both accounting for the *s*-nuclei from Sr to Pb for suitable choices of only two parameters.

In particular, starting with pure Fe seeds and adopting an exponential distribution of neutron exposures,

$$\rho(\tau) = \frac{G N_{56}^{\odot}}{\tau_0} e^{-\frac{\tau}{\tau_0}}, \tag{1.4}$$

so that $\rho(\tau)d\tau$ represents the number of Fe seeds exposed to an integrated flux between τ and τ + dτ, one can obtain an analytical solution for the set of Equations 1.3, yielding (Clayton & Ward 1974)

$$\sigma(A)N_s(A) = G N_{56}^{\odot} \tau_o \Pi_{i=56}^{A} \left(1 + [\sigma(i)\tau_0]^{-1}\right)^{-1} \tag{1.5}$$

A fit to the experimental σN curve then provided values for the fraction G of solar Fe that had been irradiated and the mean neutron exposure τ_0.

The success of this solution actually lead to the idea that each one of the three *s*-process components initially assumed to exist had to provide an exponential $\rho(\tau)$ (Clayton & Ward 1974). The *main* component was characterized by a value of τ_0 initially estimated around 0.2

mbarn^{-1}. This value was gradually increased over the years, reaching about 0.30 mbarn^{-1}, due to continuous improvements in the nuclear parameters (see Käppeler, Beer, & Wisshak 1989). The *weak* component was characterized by τ_0 = 0.06 mbarn^{-1}, while the *strong* one was found to need τ_0 = 7 mbarn^{-1}. These different values of the mean neutron exposure also explain the names given to the three components. It is here important to notice that the fortune of the exponential distribution is actually due only to its being a simple analytical formulation. In reality, any simple mathematical representation for $\rho(\tau)$ is totally insufficient (see, e.g., for the weak component Raiteri et al. 1993, and for the main component Gallino et al. 1997 and Arlandini et al. 1999).

After the basic ideas of the classical analysis were put forward, Ulrich (1973) showed how the final evolutionary phases of stars with moderate mass ($M \leq 8\ M_\odot$) could approximately provide exponential distributions of neutron exposures. He showed that this result is obtained when the neutron sources are activated in red giants during the late AGB phases, in the intermediate convective zones developing periodically as a consequence of sudden thermal instabilities in the He-burning shell (*thermal pulses*; hereafter TP). The most straightforward way to get neutrons in these He-rich layers includes the transformation of initial CNO nuclei first into ^{14}N (as accomplished by H-burning), and then into ^{22}Ne through the reaction chain ^{14}N(α,γ)^{18}F($\beta^+\nu$)^{18}O(α,γ)^{22}Ne, followed at somewhat higher temperatures by the activation of the ^{22}Ne(α, n)^{25}Mg reaction. For several years the main component was therefore ascribed to AGB stars sufficiently massive to develop, in TPs, the high temperatures needed to burn ^{22}Ne ($T \geq 3.5\times10^8$ K). This occurs for $8 M_\odot \geq M \geq 4\ M_\odot$, i.e. for the so-called intermediate-mass stars. This line of research was pursued in particular by Icko Iben and coworkers (see, e.g., Iben 1975; Truran & Iben 1977; Iben & Truran 1978; Iben & Renzini 1983).

1.3 Success and Crisis of the Classical *s*-Process Analysis

1.3.1 The Build-up of the Classical Scenario

The "classical" analysis rapidly became a sophisticated tool, where reaction branchings, like those occurring at crucial isotopes (such as ^{79}Se, ^{85}Kr, ^{64}Cu, ^{151}Sm), also could be treated (Ward, Newman, & Clayton 1976; Ward 1977). Application of the branching analysis to specific ramifications of the process was since then used for inferring the stellar parameters (average neutron density, temperature, electron density). It was also shown by Ward & Newman (1978) that the branchings held information on the pulsed nature of the neutron flux. An account of the phenomenological approach in various stages of its development can be found in Käppeler et al. (1982, 1989), Mathews & Ward (1985), and Meyer (1994).

Over the years, the nuclear parameters became so precise, on average, that the phenomenological approach based on an exponential distribution started to show its limits. Recent studies on neutron capture cross sections in the Nd–Sm region, and on their application to the analysis of branchings, finally showed that the *s*-process, as modeled directly in stellar conditions, can reach a higher level of accuracy than the classical analysis; this is due to the fact that real neutron distributions are complex, time dependent, and not really suitable for simple analytical formulations (Arlandini et al. 1999).

The combined information coming from detailed calculations in stellar models and from the phenomenological analysis of the *s*-process also showed that the ^{22}Ne(α, n)^{25}Mg source in intermediate-mass stars suffers for serious problems. Indeed, the neutron densities reached in TPs through ^{22}Ne-burning are rather high (above 10^{10} cm^{-3} for temperatures in excess of $T = 3.5 \times 10^8$ K). This implies a *n*-irradiation intermediate between the *s*- and the *r*-process (Despain 1980), in which the reaction network becomes rather complex and many branchings along the *s*-path are open. This inevitably leads to a nonsolar distribution of *s*-isotopes, and especially to excesses in the neutron-rich nuclei, like ^{86}Kr and ^{96}Zr.

Spectroscopic and photometric observations (especially on Magellanic Cloud red giants) soon confirmed that AGB stars enriched in *s*-elements (and in C, the main product of partial He burning) cannot be identified with intermediate-mass stars, where TPs reach a temperature sufficient to burn ^{22}Ne efficiently. Indeed, the observed luminosities are in general lower than in intermediate-mass stars (Blanco, McCarthy, & Blanco 1980). Moreover, in most AGBs Mg isotopes show a solar mix, contrary to the expectations of ^{25}Mg enhancement by the ^{22}Ne(α, n)^{25}Mg reaction (Clegg, Lambert, & Bell 1979; see also Karakas & Lattanzio 2004). On these problems, see Wallerstein & Knapp (1998) and Busso et al. (1999) for recent reviews.

1.3.2 *s*-Processing From ^{13}C Burning

The above problems eventually induced various authors to reconsider the conditions for the activation of the alternative source ^{13}C(α, n)^{16}O in low-mass stars. The main difficulty concerning this reaction is that of finding some mixing mechanism to inject a small amount of hydrogen from the envelope into the intershell region, where, at hydrogen re-ignition, they would be captured by the abundant ^{12}C, producing ^{13}C.

Various physical mechanisms have been proposed to solve the problem of proton ingestion (Iben 1981; Iben & Renzini 1982a,b; Hollowell & Iben 1988; Herwig, Blöcker, & Schönberner 1997; Langer et al. 1999; Cristallo et al. 2001; Denissenkov & Tout 2003; Cristallo, Gallino, & Straniero 2004). None of them, however, can prove from first principles the existence of proton fluxes in the C-rich zones. As a matter of fact, in most calculations of recent years the extent of the proton-enriched layers and/or the ^{13}C concentration in them have been assumed as free parameters to be calibrated by observational constraints.

The first models of ^{13}C burning in AGB stars assumed that the layers enriched in ^{13}C (the so-called ^{13}C-pocket) could be ingested by the subsequent pulse and burned at the typical temperature of 1.5×10^8 K (Gallino et al. 1988; Käppeler et al. 1990). In such pulses, when the intershell convection subsequently reaches its maximum extent and the temperature increases to about 3×10^8 K, the ^{22}Ne source is marginally activated, providing a second small neutron burst of relatively high peak neutron density. This neutron burst was recognized to account for several details of the solar *s*-process abundance distribution, mainly for nuclei depending on reaction branchings for which the phenomenological approach suggests a relatively high temperature in the production zone (Käppeler et al. 1989, 1990).

In the last decade, new stellar model calculations for the AGB phases by Straniero et al. (1995, 1997) showed instead that, whichever is the abundance of ^{13}C produced in the intershell, it burns locally in the radiative layers of the He intershell before a new convective pulse develops. The thermal conditions are rather different from those established inside the pulses; in particular, the temperature is lower [$(0.8-0.9) \times 10^8$ K], and the average neutron density never exceeds 1×10^7 n cm^{-3} (Gallino et al. 1998). Then the pocket, now highly *s*-enhanced, is engulfed in the convective pulse. The *s*-elements are therefore diffused over the whole He intershell and slightly modified by the marginal activation of the ^{22}Ne source.

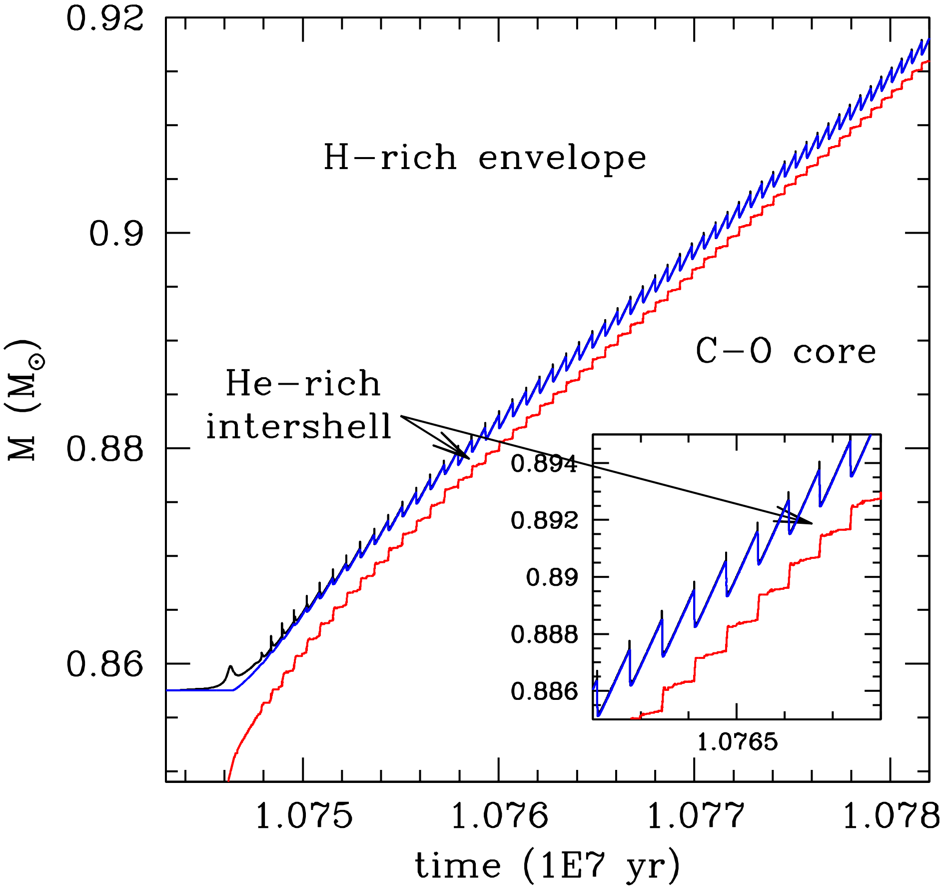

Fig. 1.1. Temporal evolution of the mass coordinates of the He-burning shell (lower line), of the H-burning shell (intermediate line), and of the inner border of envelope convection (upper line), for an AGB model with $M = 5\ M_{\odot}$ and $Z = 0.02$.

They are then partially brought to the surface during the following TDU episode. Such a scheme has been confirmed by all recent computations (Herwig et al. 1997; Goriely & Siess 2001; Lugaro et al. 2003). Before entering into the details of the ensuing *s*-process features, let us first outline the present scenario of the AGB evolution, as emerged in recent years.

1.4 AGB Models: Features and Uncertainties as a Function of Mass

The temporal evolution of the internal structure of a 5 $M_{\odot}$ with solar metallicity during the AGB phase is shown in Figure 1.1 The C-O core, whose pressure is mainly provided by degenerate electrons, is surrounded by a thin He intershell, the He-rich zone located between the He- and the H-burning shells. The convective H-rich envelope extends from the surface down to a layer located very close to the H-shell. After each TP the base of the convective envelope penetrates into the top layers of the He intershell (TDU), carrying fresh ^{12}C and *s*-process isotopes to the surface.

1.4.1 Uncertainties on Mass Loss and Convection

One of the most severe uncertainties still affecting AGB models concerns mass loss. The duration of the AGB phase and the number of TPs, the amount of mass dredged up, the impact of stellar winds on interstellar abundances, and many other important predictions depend on the assumed mass loss rate. The available data indicate that this rate ranges between 10^{-8} and 10^{-4} $M_{\odot}$ yr^{-1} (Kastner et al. 1993; Loup et al. 1993). Studies of Mira and semiregular variables show that stellar winds do not increase monotonically with time, and the star certainly encounters variations in its mass loss efficiency (Marengo et al. 1999; Marengo, Ivezić, & Knapp 2001), until a final violent (perhaps dynamical) envelope ejection occurs. One has to notice that a common finding of models is that immediately after a TP, during a phase of quiescent He-burning, the ratio of the gas pressure to the radiation pressure (β) decreases in a thin layer located around the H/He discontinuity. Sweigart (1999) found that, when the envelope is reduced to a sufficiently low mass (the exact value depending on the core mass and metallicity), β approaches 0. Then, the local stellar luminosity exceeds the Eddington luminosity and the whole envelope becomes dynamically unstable. Recently, this finding was independently confirmed in models of a 5 $M_{\odot}$ star at $Z = 0.02$ (Straniero et al. 2000). At the moment, however, one cannot say if this instability will grow indefinitely, up to the complete envelope removal, thus giving rise to the formation of a planetary nebula.

A second important uncertainty is related to the actual extension of the convective zones. Difficulties are met when the internal boundary of the convective envelope approaches regions of varying composition. In this case any perturbation, even small at the beginning, may propagate the convective instability toward the interior. In fact, as noted by Becker & Iben (1979), Castellani, Chieffi, & Straniero (1990), and Frost & Lattanzio (1996), if the H-rich convective envelope enters a region progressively enriched in He, a discontinuity of the radiative gradient forms at the interface between stable and unstable layers. This occurs because the H-rich envelope has a significantly larger opacity than the He-rich layer immediately below it. In such a case, if any mixing occurs beyond the inner border of the convective envelope, the local hydrogen abundance rises, the opacity (and the radiative gradient) grows, and the layer becomes unstable to convection. A similar situation is encountered at the outer edge of the convective core during central He-burning (Paczyński 1970; Castellani, Giannone, & Renzini 1971). Castellani et al. (1985) named this phenomenon *induced overshoot* (i.e. induced by the chemical discontinuity that forms at the boundary of a convective region), to be distinguished from *mechanical overshoot* (i.e. the mixing caused by the convective elements, which preserve a finite velocity outside the unstable region).

As far as the evolution before the TP-AGB phase is concerned (e.g., the second dredge-up, which takes place during the early AGB stages in intermediate-mass stars), the overall impact of overshoot phenomena is generally small (Castellani, Marconi, & Straniero 1998). On the contrary, Frost & Lattanzio (1996) found that the inclusion of a moderate overshoot strongly increases the efficiency of the TDU (see also Herwig et al. 1997; Herwig 2000; Cristallo et al. 2001). A change in the strength of the TDU not only modifies the surface composition of an AGB star, but greatly affects its physical properties. The comparison of model predictions with spectroscopic and photometric observations of AGB stars may help to verify the efficiency of this phenomenon and, in the long term, to calibrate mixing phenomena in stellar models. In this respect, despite the mentioned uncertainties, full stellar evolution models can now be used to provide the yields from AGB stars necessary to compute the chemical evolution of galaxies: for many years this task has been performed instead through semi-analytic or synthetic AGB models (Van der Hoek & Groenewegen 1997; Marigo 2001; see also Mollá, Gavilán, & Buell 2004).

1.4.2 Evolutionary Path as a Function of Mass

Present-generation AGB stars have masses larger than 0.8 – 0.9 $M_\odot$ (the main sequence lifetime of less massive stars is longer than the age of the Universe). The upper mass limit for AGB stars marks the inferior mass limit for "massive" stars, those which, after He exhaustion in the core, burn C, Ne, O, and Si, form a degenerate iron core, and eventually collapse. The precise value of this limit is not well defined. It has been long understood that all stars with mass below 7–8 $M_\odot$ should skip C burning, due to the huge energy loss by plasma neutrino emission, which cools their central region (Schwarzschild & Härm 1965). These stars are the progenitors of C-O white dwarfs. However, slightly more massive stars, in the range 9–10 $M_\odot$, can ignite carbon in degenerate conditions, but, once a degenerate O-Ne-Mg core is built, become thermally pulsing AGB stars (Ritossa, García-Berro, & Iben 1996). These stars may produce a massive O-Ne-Mg white dwarf (Domínguez, Tornambè, & Isern 1993) or may collapse before the beginning of the AGB phase (Miyaji & Nomoto 1987).

Even below 8 $M_\odot$ the AGB evolutionary scenario and related nucleosynthesis significantly change with the mass of the star. In the following we review the properties of AGB stars with different initial mass. The mass intervals reported below are appropriate for solar composition (i.e. $Z = 0.02$, $Y = 0.28$). The quantitative results have been derived from recently published AGB models computed by several authors, in particular Lattanzio et al. (1996), Forestini & Charbonnel (1997), Straniero et al. (1997, 2000), and Lattanzio & Forestini (1999).

$\underline{M < 1.3 M_\odot}$

At the beginning of the thermally pulsing AGB phase, the mass of the H-depleted region ($M_{\rm H}$) for these low-mass stars is about 0.55 $M_\odot$. Their envelope (already eroded by mass loss during the red giant branch) is rather small. For example, taking into account a pre-AGB mass loss in agreement with the Reimers (1975) formula with $\eta = 0.4$ (Fusi Pecci & Renzini 1975), a 1 $M_\odot$ star of solar metallicity would have at the first TP a residual envelope mass of just 0.2 $M_\odot$. During the AGB this envelope is rapidly consumed, from the top by further mass loss and from the bottom by H-shell burning, so that only few TPs are possible before the envelope mass drops below the minimum threshold allowing a red giant star structure (about 0.001 $M_\odot$). For 1 $M_\odot$ models about 10 TPs are expected (with an average mass loss of 10^{-7} $M_\odot$ yr^{-1}). However, the TDU does not take place and the envelope composition remains frozen at the composition reached after the red giant branch.

$\underline{1.3 \leq M/M_\odot < 2}$

The core mass at the first TP is more or less the same as before, but the envelope mass is larger. After a few TPs (in any case fewer than 8–9) the core mass reaches about 0.6 $M_\odot$, and a moderate TDU takes place. The surface composition changes: C and *s*-process elements are enhanced. Note that the maximum temperature at the base of the convective zone generated by TPs is well below the threshold for the activation of the ^{22}Ne(α, n)^{25}Mg reaction. Then, the s-process nucleosynthesis is only powered by the ^{13}C(α, n)^{16}O reaction, which is at work during the interpulse phase. TDU continues as long as the envelope mass remains larger than about 0.4–0.5 $M_\odot$ (Straniero et al. 1997). After the envelope mass drops below this limit, the remaining few TPs occur without any TDU. In any case, when these low-mass AGB stars reach the tip of the AGB, the C/O ratio is still lower than 1. For example, a 1.5 $M_\odot$ (solar composition) star has a C/O ratio at its birth of 0.5 (Allende Prieto, Lambert, & Asplund 2002); after the first dredge-up this ratio drops to 0.35; at the end of the AGB phase TDU restores it to 0.49. Once again, we recall that the final value of the C/O ratio depends on the assumptions about mass loss (in this particular case we have used a Reimers formula with the free parameter η = 0.4) and on the efficiency of TDU. The above scenario does not consider overshoot, so that the resulting dredged-up mass should be considered as a lower limit.

$2 \leq M/M_\odot \leq 3$

These stars are probably the most efficient contributors to the main component of the s-process. They are also progenitors of intrinsic carbon stars observed in the Galaxy and in the Magellanic Clouds, as we shall see later. Similarly to what occurs at lower masses, TDU starts after a few TPs, when the core mass attains 0.6 $M_\odot$. However, due to the larger envelope, stronger TDU episodes take place. The amount of dredged-up material may be as large as half the (He-C-s)-rich region. The TDU phase continues up to the C star stage (C/O>1) and beyond. The main source of neutrons is from the ^{13}C(α, n)^{16}O reaction. The ^{22}Ne(α, n)^{25}Mg reaction is only marginally activated at the peak temperatures of the most advanced TPs, near 300 $\times$ 10^6 K. Nonetheless, it has important effects on those reaction branchings that are sensitive to the neutron density and temperature conditions.

$3 < M/M_\odot < 5$

These stars start the TP-AGB phase with a rather large core mass. A 5 $M_\odot$ model, for example, has a core mass at the first TP of about 0.86 $M_\odot$. A negligible amount of mass loss affects the pre-AGB evolution, so that the initial envelope is quite massive. TDU begins very soon (after a couple of TPs). However, due to the huge dilution of the dredged-up material (few 10^{-4} $M_\odot$ are mixed with a few $M_\odot$ of envelope), a rather slow change of the surface C/O ratio is expected. After a few TPs, the temperature at the base of the convective zones generated by the TPs reaches 3.5 $\times$ 10^8 K, and the ^{22}Ne(α, n)^{25}Mg neutron source is activated efficiently. On the contrary, a less efficient ^{13}C(α, n)^{16}O reaction is expected. In fact, the larger the core mass, the smaller the He intershell region is: for a 5 $M_\odot$ star this layer is about one order of magnitude smaller than for of a 2 $M_\odot$ model. Correspondingly, the amount of material dredged up and the extension in mass of the ^{13}C pocket are expected to be reduced by about an order of magnitude. The resulting s-process nucleosynthesis is therefore rather different with respect to the one of low-mass stars.

During the final part of the AGB, when most of the envelope mass has been lost, these stars may eventually become bright C stars. The most massive in this range (4–5 $M_\odot$) may also become Li-rich AGB stars. First of all, Be is produced by the ^{3}He(α, γ)^{7}Be reaction. This requires a temperature of at least 30 $\times$ 10^6 K. Then Li may be synthesized by the Be decay ^{7}Be(e^-,ν)^{7}Li ($t_{1/2}$ = 53 d). Note that at high temperatures Li is quickly destroyed by the reaction ^{7}Li(p, α)^{4}He. Thus, the Li production might occur only if the mixing is fast enough to move ^{7}Be to a cooler external region before electron captures take place (Cameron & Fowler 1971).

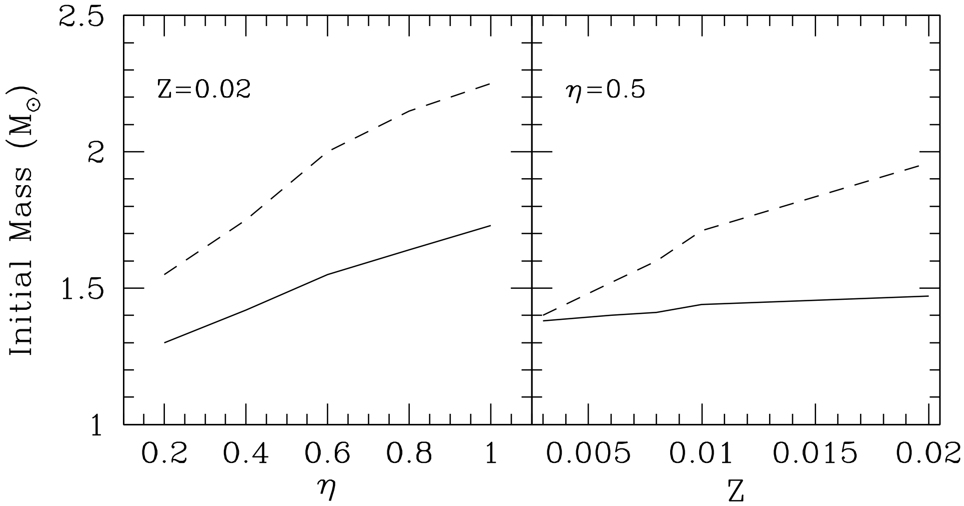

Fig. 1.2. *Left panel*: The minimum initial mass for experiencing a TDU phase (solid line) for the formation of a C star (dashed line) as a function of the η parameter in the Reimers formula for mass loss. *Right panel*: The same parameters shown in the left panel, but plotted as a function of metallicity.

$5 < M/M_\odot < 8$

The most massive AGB stars can also produce *s*-elements, mainly through the ^{22}Ne(α, n)^{25}Mg reaction activated during the TP phase. Then, *s*-elements and fresh He and C are mixed with the envelope by TDU. The relevant feature of these stars is that a complete CN burning occurs inside the convective envelope, so that the fresh C dredged up is almost totally converted into N. The occurrence of this *hot bottom burning* (Karakas & Lattanzio 2004) solves the longstanding problem of the lack of very bright C stars ($M_{\rm bol} < -6$ mag; see Iben 1981). Only for a short period before the end of the AGB phase, when hot bottom burning dies out and TDU is still active, might the surface C/O ratio increase above unity, generating very luminous C stars, which, however, should be extremely rare (Lattanzio 1998).

1.4.3 The Effect of Metallicity

The limiting masses of the above ranges decrease for decreasing mass loss rate and metallicity. This is shown in Figure 1.2, where the minimum mass for the formation of a C star and the minimum initial mass for the occurrence of the TDU are shown.

1.5 *s*-Processing in the Galaxy at Different Metallicities

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

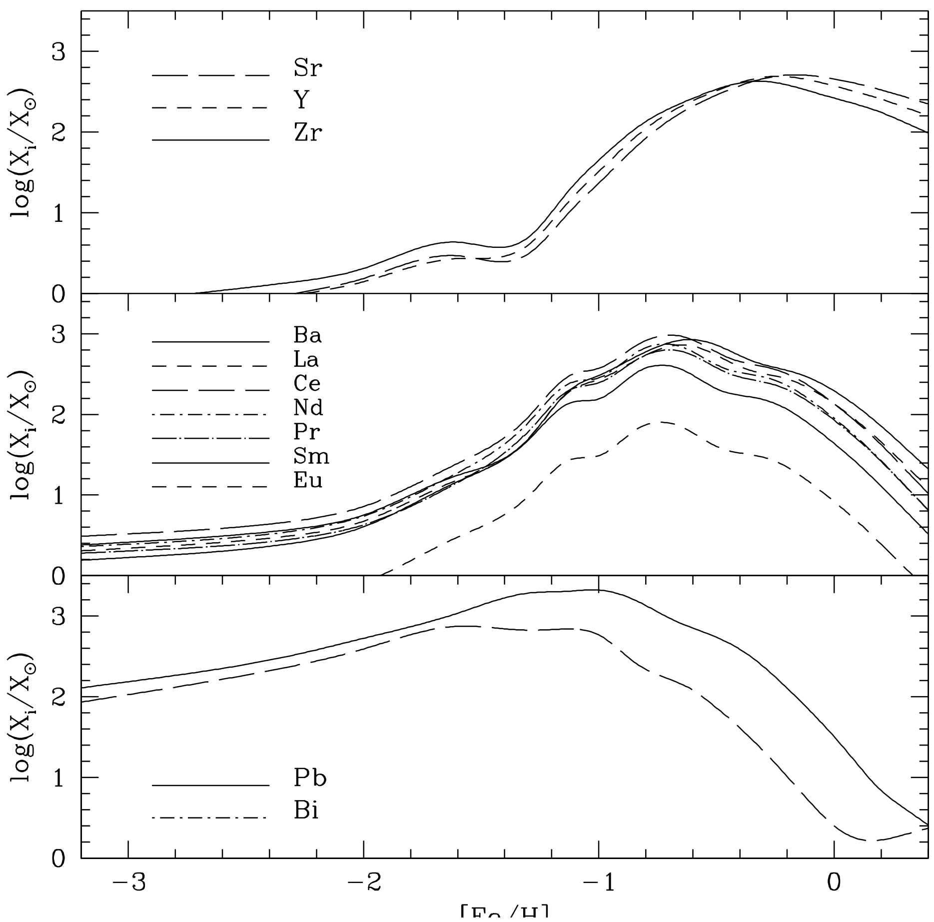

Fig. 1.3. Model predictions for the abundance of selected neutron-rich elements in the production layers of AGB stars with different metallicity. All calculations adopt the same choice for the amount of ^{13}C burnt per cycle.

inversely proportional to the metallicity. Then, starting from an AGB star of initially solar composition, the neutron exposure tends to increase with decreasing Z. This has a dramatic effect on s-process abundances of elements with different atomic mass number, as shown in Figure 1.3 as a function of [Fe/H] for Galactic disc compositions. Here [Fe/H] = log(Fe/H) – log(Fe/H)$_\odot$ is the usual logarithmic notation adopted in astronomical spectroscopy for the stellar metallicity.

With the adopted ^{13}C pocket, at solar metallicity one would produce essentially s-elements belonging to the Sr-Y-Zr peak, at the neutron magic number N = 50; decreasing Z, one would have more neutrons available per Fe seed, thus bypassing the bottleneck at N = 50 and progressively feeding elements at the second neutron magic peak, at Ba-La-Ce-Pr-Nd, with a maximum production 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. The maximum production of Pb occurs around $Z = Z_{\odot}/20$ (Travaglio et al. 2001). Eventually, for Galactic halo AGB stars with very low metallicities, all the initial Fe is efficiently converted directly to Pb, but the shortage of iron seeds becomes dominant, so that even the production of Pb decreases with metallicity. Due to this fact, *s*-process abundances are expected to decrease and eventually 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. 2004, and references therein). Summing up, the *s*-process in AGB stars of different metallicity driven by the primary ^{13}C neutron source gives rise to a wide spectrum of different abundance distributions.

The mentioned dependence of the neutron source on local mixing phenomena then leads to expectations of large star-to-star scatter in the *s*-abundance distributions, even for AGB stars of the same metallicity. On the whole, the solar system distribution of *s*-elements is clearly not a ''unique" process, but results from the integrated chemical evolution of the Galaxy, which mixes in the interstellar medium the outputs of many different stars, with yields changing with the initial metallicity, stellar mass, and maybe other physical properties.

The above discussion changes completely the traditional interpretation of the various *s*-process components. For example, the fact that at low metallicities Pb (^{208}Pb) becomes the dominant product of AGB nucleosynthesis reveals that an independent strong component (by some unknown astrophysical source) does not exist (Gallino et al. 1998; Goriely & Siess 2001; Travaglio et al. 2001). It also shows that at very low metallicity the neutron exposure cannot be monitored only by the elements of the Zr-peak and Ba-peak groups, as the neutron flux tends to accumulate on the neutron magic number corresponding to ^{208}Pb (Fig. 1.4). Moreover, at very low metallicities, the very low abundance of the Fe seeds is partly compensated by lighter, primary-like nuclei, from which the *s*-process nucleosynthesis directly starts, reproducing and crossing the Fe peak. Among such intermediate-mass neutron seeds one has to mention, in particular, ^{22}Ne and its progeny. In fact, CNO nuclei in the envelope become abundant due to the increased [O/Fe] ratio characterizing halo stars (see, e.g., Spite et al. 2004): this trend is actually continued through the thick and thin disk for metallicities lower than solar, as shown by Bensby, Feltzing, & Lundström (2004). In the CNO increase an important role is played also by the primary ^{12}C produced in the AGB phase. These CNO nuclei are mixed through the H-He discontinuity at TDU; here they are transformed into ^{14}N by shell H-burning and subsequently into ^{22}Ne by double α-captures in the early phases of a convective pulse, thus strongly increasing the concentration of the neutron source.

1.6 *s*-Processing in C(N) Stars

Probably the most important chemical anomaly of stars in the AGB phase is that many of them are carbon rich, i.e. they have a C/O ratio (by number) larger than unity in the envelope. For this reason, they are named carbon stars. As noted in previous sections, this carbon enrichment is the result of the simultaneous operation of TPs and TDU along the AGB phase that eventually transforms an O-rich star into a carbon star. In fact, the carbon content in the envelope is expected to increase along the spectral sequence of the AGB phase M$\rightarrow$MS$\rightarrow$S$\rightarrow$SC$\rightarrow$C(N type). Alternatively, this carbon enrichment could derive from a transfer of carbon-rich material in a binary system. In the first case the stars are usually named *intrinsic* carbon stars, while in the second case they are named *extrinsic* car-

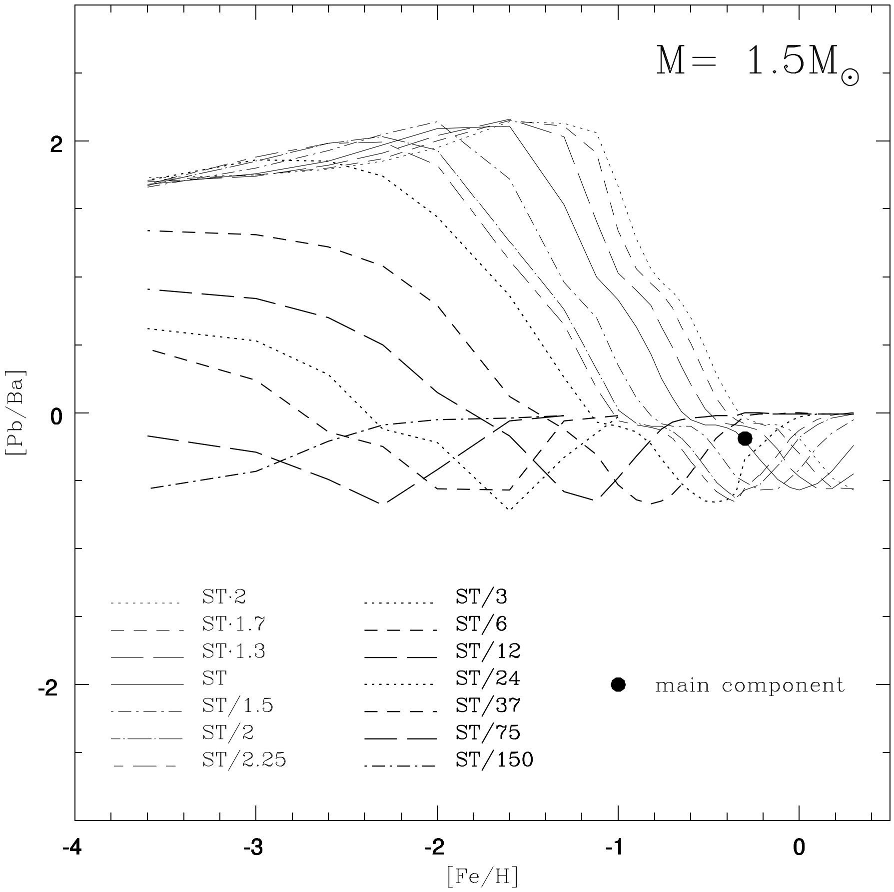

Fig. 1.4. The final envelope abundance ratio [Pb/Ba], as predicted by our AGB models for $M = 1.5\ M_{\odot}$, as a function of metallicity. The concentration of the ^{13}C source has been left to vary over a wide interval, as indicated by the labels. Here ST refers to the abundance of ^{13}C assumed as *standard* by Gallino et al. (1998), namely $4\times10^{-6}\ M_{\odot}$

bon stars. Our discussion will be concentrated on the first class. As shown before, TDU also enriches the envelope with *s*-process elements: in fact, C(N) stars are the main producers of *s*-elements in the Galaxy. They are significant contributors also to ^{12}C, ^{13}C, and rare nuclei such as ^{7}Li and ^{26}Al: these isotopes are affected not only by convective dredge-up, but also by more complex phenomena of extended mixing, or *cool bottom processes*, occurring in red giants (see, e.g., Charbonnel & Balachandran 2000; Nollett, Busso, & Wasserburg 2003; Busso, Gallino, & Wasserburg 2004; Charbonnel 2004).

C(N) stars, or normal carbon stars (Keenan 1993), represent a formidable challenge from the spectroscopic point of view. They show very crowded spectra due to their strong molecular-band absorption and low temperature. Thus, it is not surprising that until recently

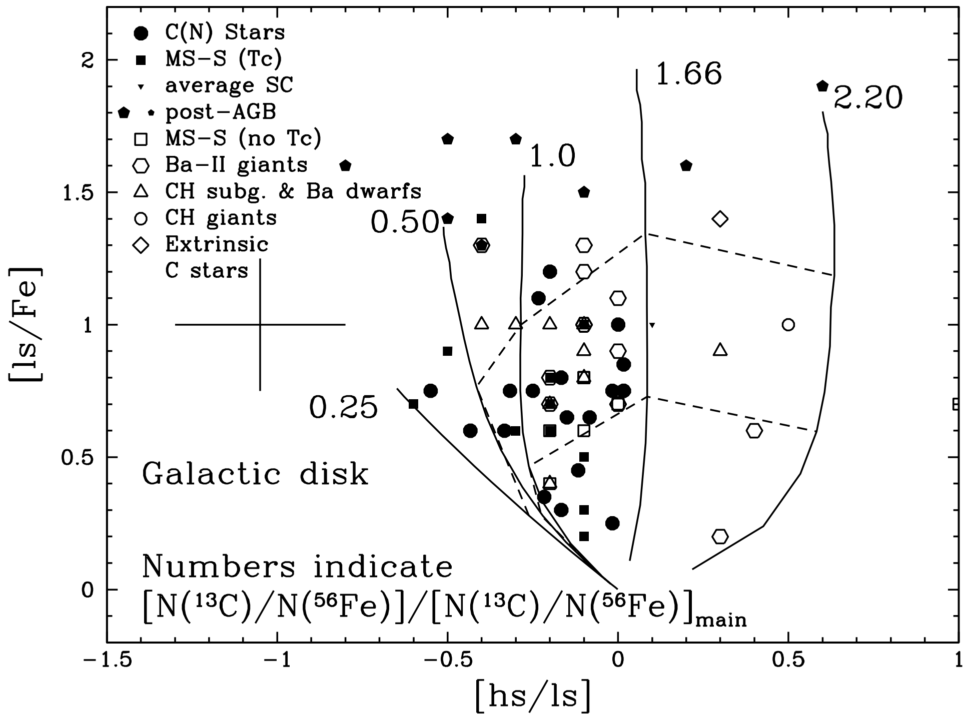

Fig. 1.5. The various symbols refer to observations of *s*-element enhancement in different classes of AGB stars at different metallicities. The curves are theoretical sequences of envelope enrichment. The number of TDU episodes increases toward the top, and dashed lines mark the occurrence of the 4th and 8th mixing episode. The curves were obtained for models with varying efficiency in the neutron captures, as monitored by the abundance ratio between the neutron source ^{13}C and Fe. C(N) stars occupy regions compatible with their being slightly more evolved than the average of S stars.

the only detailed analysis of their *s*-element abundances was that by Utsumi (1970, 1985), who found that C(N) stars are of roughly solar metallicity; he suggested that their mean *s*-element enhancements ([ls/Fe] and/or [hs/Fe])* reach a factor of 10 or more above solar. This level of enrichment would be considerably larger than for the O-rich S stars: however, it was accepted as a rather extreme outcome of the synthesis of *s* nuclei during the AGB phase. More recent studies are now available (Abia et al. 2001, 2002), based on high-resolution spectra of a more extended sample of N stars. This has caused a strong revision in the quantitative *s*-element abundances. N stars were confirmed to be of near solar metallicity, but they show on average $\langle$[ls/Fe]$\rangle = +0.67 \pm 0.10$ and $\langle$[hs/Fe]$\rangle = +0.52 \pm 0.29$, which is significantly lower than estimated by Utsumi and is more similar to S star abundances (Smith & Lambert 1990; Busso et al. 2001). This revision allowed the extension to C(N) stars of the generally good agreement between observed *s*-process abundances and theoreti-

* In the following, "ls" refers to the light-mass *s*-elements Y and Zr, and, "hs" refers to the high-mass *s*-elements Ba, Nd, La, and Sm.

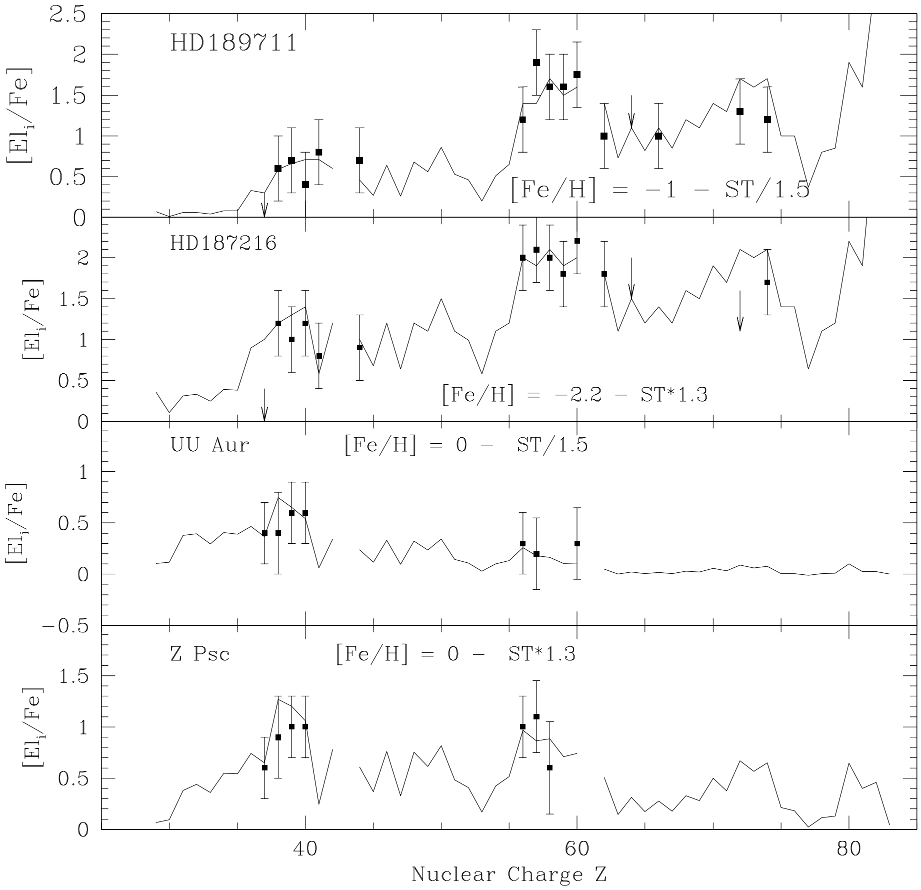

Fig. 1.6. Observed and theoretical distributions of *s*-elements at the surface of AGB stars, when the abundance ratio by number of C/O reaches unity. The models adopted are those discussed in §1.5.

cal predictions of *s*-process nucleosynthesis in AGB stars (Gallino et al. 1998; Busso et al. 1999). Such comparisons confirm also for C(N) stars the existence of an intrinsic spread in the abundance of ^{13}C burnt, and allow us to place observed AGBs with different *s*-process and carbon enrichment along simple evolutionary sequences (Fig. 1.5). In these sequences only 1−2 pulses separate a typical S star from a C(N) star. During this short time interval the spectroscopic appearance changes drastically because C-based opacities start to dominate, but the *s*-element composition is only slightly affected. Later, as the star evolves along the AGB and TPs and TDU continue operating, more carbon and *s*-elements are dredged up into the envelope. Eventually, the C/O ratio may exceed unity by a consistent amount, before stellar winds terminate the evolution; but the simultaneous increase of mass loss rates forms a thick and dusty circumstellar envelope obscuring the star at optical wavelengths.

This scenario might explain not only the large C abundances observed in some planetary nebulae (Parthasarathy 1999), but also the apparent *gap* in the level of *s*-element and carbon enhancement between N stars and post-AGB stars (Van Winckel & Reyniers 2000; Reyniers & Van Winckel 2004). We cannot "see" carbon stars with a C/O ratio largely exceeding unity. The fact that we now understand the evolutionary status and the composition of C(N) stars is confirmed by the possibility of obtaining satisfactory models of their detailed photospheric abundances, through *s*-process computations in AGB models that also account for dredge-up and mass loss. Examples of such models for C(N) stars of different metallicities are shown in Figure 1.6.

Another important result inferred from observations of C(N) stars and from the properties of the *s*-process path at reaction branchings is an estimate of the initial mass of C(N) stars. As noted previously, in low-mass stars the major neutron source is ^{13}C. If C(N) stars were of intermediate mass, ^{22}Ne would be favored as a neutron donor by the higher temperature in TPs. Because of the very different neutron density provided by the two neutron-producing reactions, different compositions are expected from them, especially for nuclei depending on the complex reaction branching at ^{85}Kr. The simplest example of this is displayed by the ratio Rb/Sr. As the isotope ^{87}Rb is strongly fed only at high neutron densities, this ratio increases for increasing n_n, hence for increasing contributions of the ^{22}Ne(α, n)^{25}Mg reaction to neutrons. On this basis Abia et al. (2001) showed that, since C(N) stars observed so far always show low values of the Rb/Sr ratio, their neutron captures must be controlled by ^{13}C(α, n)^{16}O and they must therefore be of low mass ($M \leq 3\ M_{\odot}$).

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