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The ^{13}C Pocket in Low-Mass AGB Stars

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Abstract: It is well known that thermally pulsing Asymptotic Giant Branch stars with low mass play a relevant role in the chemical evolution. They have synthesized about 30% of the galactic carbon and provide an important contribution to the nucleosynthesis of heavy elements ($A > 80$). The relevant nucleosynthesis site is the He-rich intermediate zone (less than 10^{-2} M$_\odot$), where $\alpha(2\alpha, \gamma)^{12}$C reactions and slow neutron captures on seed nuclei (essentially iron) take place. A key ingredient is the interplay between nuclear processes and convective mixing. It is the partial overlap of internal and external convective zones that allows the dredge-up of the material enriched in C and heavy elements. We review the progresses made in the last 50 years in the comprehension of the *s* process in AGB stars, with special attention to the identification of the main neutron sources and to the particular physical conditions allowing this important nucleosynthesis.

Keywords: nuclear reactions, nucleosynthesis, abundances — stars: AGB and post-AGB

1 Introduction

For a long time our understanding of *s*-process nucleosynthesis and stellar evolution advanced in parallel, but only recently they merged in a unique theory. The two stories started more or less at the same time, namely in the second half of the 1950s, with the first attempts to identify the main nuclear processes responsible for the synthesis of the elements beyond iron and with the first comprehensive picture of the physical properties of post-main-sequence evolutionary phases. It was during the 1970s that thermally pulsing Asymptotic Giant Branch (AGB) stars were identified as a promising astrophysical site for the *s* process, but only in the last decade of the 20th century it was realized how the so called main and strong components of the cosmic *s*-process (including elements between Sr and Bi) can be produced in the He-rich intershell of low-mass AGB stars. In this paper, we critically analyze the main steps of these two stories up to the most recent attempts to reach a unified theoretical scenario.

2 The Beginning: 1950–1960

In 1951, Bidelman & Keenan firstly proposed a 'parallel' spectral sequence of giant stars, including S, R, N types as well as a new possible Ba II class. Stars belonging to these spectral classes show anomalously large abundances of certain heavy elements. One year later, Merrill (1952) announced the discovery of technetium in S stars. It was a very import discovery, because Tc has no stable isotopes and, for this reason, its detection suggested that the synthesis of this element is an ongoing process in these stars.

In these same years, Sandage & Schwarzschild (1952) carried on the first models of Red Giant Stars and Salpeter (1952) proved that the $\alpha + \alpha \rightleftarrows {}^8$Be followed by ^{8}Be $+ \alpha \rightarrow {}^{12}$C processes provides the way for He burning in giant stars. The theory of stellar evolution beyond the main sequence was born.

The Cameron (1955) paper entitled 'Origin of anomalous abundances of the elements in Giant Stars' contains the first suggestion that neutron captures by iron seed nuclei are a fundamental nucleosynthesis process. He identified the ^{13}C$(\alpha, n)^{16}$O as a promising neutron source in giant stars. A naive evolutionary scenario was depicted: as a by-product of shell H burning via the CNO cycle, some ^{13}C is left in the hot He-rich core of giant stars, where the ^{13}C$(\alpha, n)^{16}$O reaction and the consequent *s*-process nucleosynthesis take place. However, Fowler, Burbidge & Burbidge (1955) argued that too few neutrons would be available in that case (namely 1.4 neutrons per seed), because of (1) the relatively low amount of ^{13}C in the ashes of the CNO cycle and (2) the strong neutron poisoning of ^{14}N, whose neutron capture cross section is particularly large. A further problem concerned how these heavy elements, once produced in the stellar core, become observable at the stellar surface. In order to overcome these problems, Cameron (1957a) for the first time introduced the need for an interplay between mixing and nucleosynthesis. In particular, he claimed that mixing of a few protons could take place between the H-rich envelope and the He-rich core of low-mass stars during the so called core He flash. This mixing would allow the production of fresh ^{13}C (via the ^{12}C$(p, \gamma)^{13}$N$(\beta^- \nu)^{13}$C chain) in the core and, at the same time, the dredge-up of heavy elements. Actually, such a mixing occurs only if the entropy

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barrier set up by the H-burning shell is switched off, as happens in extremely metal poor stars (e.g. Hollowell, Iben & Fujimoto 1990; Picardi et al. 2004). In the same paper, Cameron also noted that since the neutron capture by ^{14}N mainly proceeds through the p channel, rather than through the γ channel, the neutron poisoning effect of the ^{14}N is partially reduced to a proton recycling. These protons, indeed, induce an additional production of ^{13}C. Figure 2 of the Cameron paper is particularly enlightening. It shows how a substantial overproduction (10^3 times the initial abundance) of light s elements (ls), like Sr, can be obtained with a relatively low number of neutrons per seed (about 10), while the same overproduction of heavy s elements (hs), like Ba, and Pb require about 15 and 20 neutrons per seed, respectively. As a matter of fact, only recently have we understood that the strong component of the s process most likely comes from low-metallicity AGB stars, where the lower amount of iron favors the production of lead (e.g. Busso, Gallino & Wasserburg 1999).

Another important indication can be found in Cameron's seminal paper (1957b). When discussing the spectra of R And, an S star, he explained how the detection of strong niobium lines, unlike the detection of Tc lines, is evidence that neutron capture nucleosynthesis is not an ongoing process in this star: indeed, ^{93}Nb, the only stable isotope of niobium, is destroyed by neutron capture during the AGB, but, later on, it is produced by the delayed ^{93}Zr decay (half-life 1.6×10^5 yr). Hence, an appreciable fraction of this half-life has passed since neutron production ceased in the material that has been mixed to the surface of R Andromedae. Later on, Cameron (1960), proposed $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$ as a possible alternative neutron source.

3 The Golden Age of the Classical Analysis: 1961–1980

A fundamental step ahead was taken by Clayton (1961; see also Seeger, Fowler & Clayton 1965), who demonstrated that a superposition of several neutron exposures is required to reproduce the experimentally observed abundance distribution of the s-process isotopes in the solar system. As an example, Seeger et al. (1965) proposed an exponential distribution of neutron exposures. This simple mathematical law was widely accepted for more than 20 years as the paradigm of the so called s-process classical analysis.

Meanwhile, the availability of new computer facilities in the USA, Japan and Europe allowed the development of accurate models of the advanced phase of stellar evolution, in particular the AGB phase. So, Weigert (1966) and Schwarzschild & Härm (1967) discovered the occurrence of thermal pulses in the AGB phase. Powered by the periodic ignition of He shell flashes, a series of convective zones mix the products of the 3α reactions (essentially carbon) through the He-rich layer. Ulrich (1973) noted that, if a potential neutron source is activated during a thermal pulse, the partial overlap of successive convective shells naturally leads to an exponential distribution of neutron exposures, precisely as suggested by Clayton.

A simple mathematical law appeared appealing for the classical analysis and, in addition, AGB models provided a natural support to this choice. Then, by applying Occam's razor, the paradigm of the s process was definitely established. The astrophysical site of the s process was identified in the convective He-rich zone of thermally pulsing AGB stars. The resulting thermal energy is, in this case, about 25 KeV, corresponding to the typical maximum temperature at the bottom of the convective zone generated by a thermal pulse (about 3×10^8 K). Hence, nuclear physics investigations were concentrated on this energy range (see Bao & Käppeler 1987).

4 The Search for the Main Neutron Source, Successes and Failures: 1980–1993

The last piece of the puzzle, the neutron source(s), was still lacking. Meanwhile, the classical analysis grew and significant progress was made in modeling AGB stars (Iben 1975; Sugimoto & Nomoto 1975; Truran & Iben 1977). In particular, it was realized that when the thermal pulse starts, ^{22}Ne is synthesized from ^{14}N left behind by H burning during the interpulse period, after two α captures and one β decay. At its maximum size, the convective zone in the He-rich intershell extends from the position of highest He-burning rate to just below the external border of the H-exhausted core, but no further. Then, enough neutrons could be released by the $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$, but only if $T \geq 3.5 \times 10^8$ K. This condition is achieved in massive AGB only ($M > 5\,\mathrm{M}_\odot$). Following the disappearance of the convective shell, the base of the convective envelope extends down to the outer portion of the region previously contained into the convective shell and allows the mixing of the material enriched in C and heavy elements within the envelope (the so-called 'third dredge-up' or TDU).

However, the fact that the $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$ is very marginally active in low-mass AGB stars of nearly solar metallicity, because the maximum temperature in the He-rich zone is too low, is at odds with the evidence that the bulk of the s-enriched AGB stars in the disk of the Milky Way are low-mass stars. The prediction of extant stellar models is that less than 1 neutron per ^{56}Fe is produced by the ^{22}Ne neutron source! The final word against the ^{22}Ne neutron source was pronounced by Busso et al. (1988). On the base of stellar models of massive AGB stars, as computed by means of the FRANEC code in the version described by Chieffi & Straniero (1989) they concluded that the reaction $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$ is unable to give rise to a solar distribution of s nuclei.

An alternative neutron source capable of providing a suitable neutron flux even in low-mass AGB stars, was actually searched for since the beginning of the 1980s. Sackmann (1980) suggested the possible occurrence of proton ingestion into the He convective shell at its maximum size, but Iben (1982) showed that no mixing of protons occurs during the thermal pulse because at that time the H-burning shell is very efficient, producing a substantial entropy barrier. On the other hand, Iben & Renzini (1982) noted that, as a consequence of the huge expansion of the envelope caused by the He-shell flash, a few hundred years after the disappearance of the He-rich convective zone the H-burning shell dies down, a condition more favorable for the downward proton diffusion. They proposed that, at that epoch, a semiconvective layer may form, driven by an (assumed) peak of the carbon opacity around $T = 10^6$ K and that the resulting (partial) mixing may induce a certain proton leak from the envelope down to the top of the He-rich intershell. Later on, when the temperature at the top of the He-rich intershell rises, a ^{13}C pocket may form. In the Iben & Renzini original scenario the *s* process occurred when the ^{13}C pocket is engulfed into the convective zone generated by the subsequent thermal pulse and it is burned at relatively high temperature through $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ (see also Hollowell & Iben 1989). In this case, up to 26 neutrons per ^{56}Fe are available at solar metallicity and the neutron density is about 10^9–10^{10} neutrons per cm^3. The first complete *s*-process nucleosynthesis calculation based on stellar inputs was obtained by Gallino et al. (1988). By adopting the Hollowell & Iben model, they showed that the $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ reaction provides, at variance with the $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$, a neutron source capable of reproducing the solar system distribution of *s*-only isotopes with $A > 80$.

In spite of these successes, the crisis was, once again, knocking at the door. The advent of high-resolution spectroscopy era allowed powerful tools to probe the physical conditions at the *s*-process site (Smith & Lambert 1986; Malaney 1987; Malaney & Lambert 1988; Busso et al. 1995; Lambert et al. 1995; Abia et al. 2001). These studies used important branching ratios sensitive to the physical condition at the *s*-process site, like the temperature or the neutron density (see the Käppeler et al. contribution to this volume). In particular, the Rb/Sr ratio, which is influenced by the branching at ^{85}Kr, is sensitive to the neutron density. These studies showed that the low Rb abundance, compared to Sr, as found in many S, C and Ba stars, implies a quite low neutron density (less than 10^8 neutrons per cm^3). This is incompatible with any *s*-process scenario in which the neutron irradiation takes place in the convective zone generated by the thermal pulse. Similarly, the low value of the solar system isotopic ratio ^{96}Zr/^{90}Zr indicates that the main *s*-process nucleosynthesis should occur at low neutron density.

Also the stellar theory was reaching a dead-end. Bazan & Lattanzio (1993), investigating the energetic feedback occurring when the ^{13}C pocket is engulfed into the convective shell and the *s*-process takes place, found likely substantial alterations of the thermal pulse characteristics and those of the related nucleosynthesis. In particular, they found particularly high neutron density (10^{10} cm^{-3}), implying an overproduction of both Rb and ^{96}Zr, in clear contrast with the observation.

5 Toward a Unified Approach to Stellar Evolution and Nucleosynthesis in AGB Stars

The solution of the stellar *s*-process enigma was found, perhaps by chance, by Straniero et al. (1995). The aim was to check, by means of the FRANEC code, the dramatic result obtained by Bazan & Lattanzio. Following the original suggestion by Iben & Renzini (1982), Straniero et al. (1995) assumed that after the 14th dredge-up episode of a 3-M$_\odot$ model of solar metallicity, a small number of protons (10^{-6} M$_\odot$) reached the top of the He-rich zone. They then followed the evolution of these protons through the whole interpulse period and up to the development of the subsequent thermal pulse. As expected, at H reignition a ^{13}C pocket rapidly formed, but during the interpulse large enough temperature were developed for the $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ reaction to be activated well before the end of the interpulse. In practice, the ^{13}C burning and the *s* process occur in radiative conditions and before the onset of the subsequent thermal pulse. The neutron density is only 10^6–10^7 cm^{-3} and the typical thermal energy is just 8 KeV. The radiative *s*-process timescale is quite long (a few 10^4 yr) compared with the convective *s*-process timescale (a few years). New stellar models of low-mass stars ($1 \leq M/M_\odot < 3$) were computed in the next 2 years, strengthening the new scenario of the radiative ^{13}C burning (Straniero et al. 1997). Gallino et al. (1998) carried out the full nucleosynthesis calculation based on these new models. The mass and the profile of ^{13}C within the pocket were treated as free parameters. The Gallino ST case (corresponding to 4×10^{-6} M$_\odot$ of ^{13}C) provided the best reproduction of the main *s*-process component in the solar system. In particular, the Rb/Sr and ^{96}Zr/^{90}Zr problems as well as the energetic feedback problem found by Bazan & Lattanzio were removed. It is worth to note that the new stellar scenario for the *s* process was, in a certain sense, much more complex than previously believed. In fact, the different layers within the pocket undergo different neutron exposures, because of their different temperature and ^{13}C abundance. These differences are averaged when the *s*-rich pocket is engulfed into the convective zone generated by the subsequent thermal pulse, but due to the partial overlap with previous convective zones, the freshly synthesized material is also mixed with the material processed by previous *s*-process episodes. In addition, the marginal activation of the $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$ may furtherly modify the heavy element distribution. As pointed out by Arlandini et al. (1999), the classical *s*-process analysis based on the simple exponential distribution of the neutron exposures is clearly unable to describe such a more complex nucleosynthesis scenario.

More recently, Busso et al. (2001) and Abia et al. (2002) showed how the ratios between the first (l*s*), the second (h*s*) and the third (Pb) *s*-process peaks are sensitive to the mass of ^{13}C in the pocket. This effect is illustrated in Figure 1. On this basis, Gallino and his team concluded that a certain spread in the ^{13}C mass is required to explain the observed spread of [h*s*/l*s*] and [Pb/h*s*].

6 Conclusions

In the last decades several hypotheses have been advanced to explain the origin of the ^{13}C pocket and quantitatively predict its mass and chemical profile, The most promising

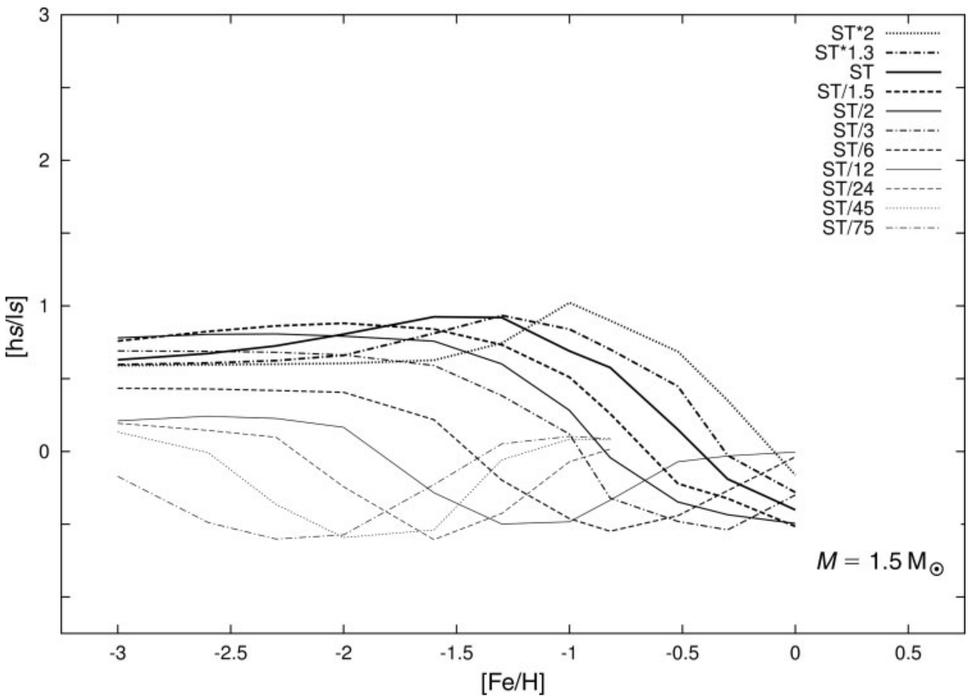

Figure 1 Variation of the spectroscopic index [h*s*/l*s*] as a function of [Fe/H] for different mass of ^{13}C in the pocket (see text for the definition of the ST case).

one was that of Herwig et al. (1997; see also Herwig 2000), where a parameterized convective overshoot was adopted, based on prescriptions derived by 2D hydrodynamical calculations of stellar convection. They obtained ^{13}C pockets with mass of the order of 2–4 $\times$ 10^{-7} $M_\odot$ that is 10- to 20-times smaller than the ST case defined by Gallino et al. (1998). Then Langer et al. (1999) investigated the possibility of rotational induced mixing, while Denissenkov & Tout (2003) that of a weak turbulence induced by gravity waves.

Let us discuss in more detail the problem of the physical description of the convective boundary at the time of the third dredge-up. When the convective envelope penetrates the H-exhausted core, a steep variation of the composition takes place at the convective boundary. The mass fraction of H sharply drops from about 70%, within the convective envelope, to zero, in the underlying radiative layer. The discontinuity in the composition induces a sharp variation of the radiative opacity and, in turn, an abrupt change of the radiative gradient. In these conditions, the precise location of the convective border (i.e. the limit of the region fully mixed by convection) becomes highly uncertain. A small perturbation causing a further mixing is amplified on a dynamical timescale, the radiative gradient in the radiative stable zone rises up and the convective instability moves toward the interior. This situation is commonly encountered in stellar model computations at the time of the second and the third dredge-ups (Becker & Iben 1979; Castellani, Chieffi & Straniero 1990; Frost & Lattanzio 1996; Marconi, Castellani & Straniero 1998). If the effect of such an instability may be marginal in the case of the second dredge-up, this is not true for the third dredge-up.

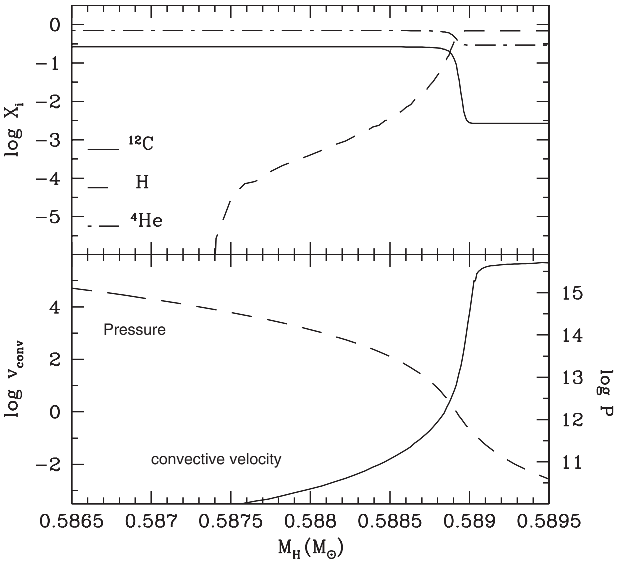

Figure 2 The boundary of the convective envelope during the third dredge-up. Lower panel: the exponential decline of the convective velocity and the sharp pressure gradient. Upper panel: chemical composition in the transition region between the convective envelope and the radiative core.

Two are the main consequences: (1) deeper dredge-ups and (2) earlier occurrence of the first TDU episode. In other word, the minimum core mass for the occurrence of the TDU is lower. The observable consequences are many and important. The C star luminosity function is shifted toward lower luminosities and the surface overabundance of heavy elements with $A > 80$ are significantly larger.

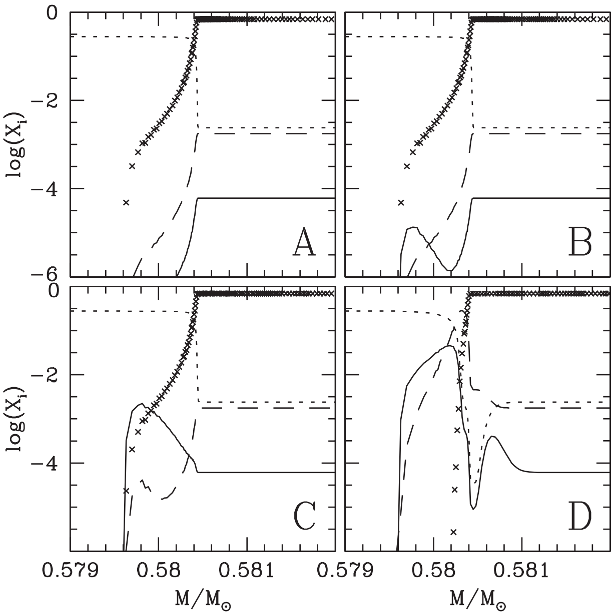

Figure 3 The formation of the ^{13}C pocket. The sequence of panels A-B-C-D shows the evolution of the chemical composition in the transition zone between the H-rich envelope and H-exhausted core. The various lines represent: H (crosses), ^{12}C (dotted), ^{13}C (solid) and ^{14}N (dashed). Panel A: the third dredge up is just occurred and the convective envelope is receeding; panel B: the temperature and the density increase, the synthesis of ^{13}C starts; panel C: where the number of protons is larger, some ^{14}N is also produced; panel D: the ^{13}C and the ^{14}N pockets are fully developed.

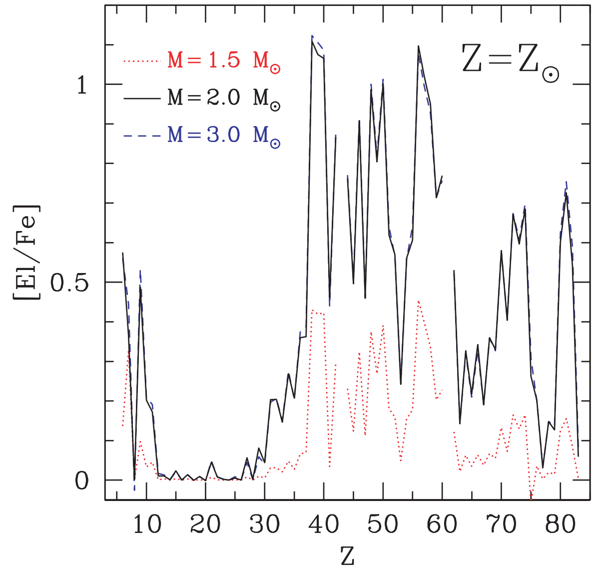

Figure 4 The surface composition at the AGB tip of 3 stellar models with solar metallicity and $M = 1.5$, 2.0 and 3.0 M$_\odot$, blue, black and red line, respectively, as obtained by means of our latest version of the stellar evolution code, which includes a full network fro H to Bi.

A more realistic description of the convective boundary than that usually adopted in extant stellar evolution code is, in principle, required. Instead of a well defined spherical surface, as obtained when the bare Schwarzschild's criterion is used, the transition between the full-radiative core (i.e. unmixed) and the full-convective (i.e. fully mixed) envelope most likely occur in an extended zone where only a partial mixing takes place, so that a smooth and stable H profile may form. The evaluation of the actual extension of this transition zone and the degree of mixing there occurring would require sophisticated and reliable hydrodynamical tools. At present, however, the inclusion of such kind of algorithms in the hydrostatic stellar evolution codes is probably a 'Mission Impossible'! So far, only limited, even if enlightening, hydrodynamical investigations have been carried out (see e.g. Herwig et al. 2006). Nonetheless, a different approach may be followed. When the convective envelope penetrates the H-exhausted core, the average convective velocity at the inner border (v, which is proportional to the difference $\nabla_{\rm rad} - \nabla_{\rm ad}$) rises up (see Figure 2). Note that this occurrence confirms the instability arising at the convective boundary during dredge-up. In order to control such an instability, in our most recent calculations of low-mass AGB stars (Straniero, Gallino & Cristallo 2006; Cristallo et al. 2009), we have assumed that at the convective border the average convective velocity drops smoothly to 0. In particular, we impose an exponential decline of v, whose steepness is given by a free parameter to be calibrated in some way:

$$v = v_{\rm bce} \exp\left(-\frac{d}{\beta H_{\rm P}}\right), \tag{1}$$

where d is the distance from the formal convective boundary (as defined by the Schwarzchild criterion), $v_{\rm bce}$ is the average velocity at the most internal convective mesh, $H_{\rm P}$ is the pressure scale height and β is a free parameter. A similar approach has been already followed by Herwig (1997), who assumed an exponential decline of the diffusion coefficient at the convective border.

The effects of the use of this algorithm on the physical and chemical properties of the dredge-up are illustrated in Figure 2. Note that in most cases since $v_{\rm bce}$ is nearly zero at a convective border, the resulting transition zone is extremely thin. On the contrary, during a dredge-up episode, owing to the growth of $v_{\rm bce}$, the transition region, where v declines smoothly to zero, becomes quite extended.

As a result, a stable H profile is left in the He-rich intershell region after the third dredge-up, whose sharpness may be changed by acting on the v decline parameter β. It is in this zone that, during the interpulse, the ^{13}C pocket forms. The total mass of ^{13}C depends on the β value. On the basis of numerical experiments made by changing the v decline parameter we found (1) the total mass of material dredged up increases with β and (2) there exists a maximum mass of ^{13}C in the pocket, as obtained for β about 0.1, roughly corresponding to the ST case found by Gallino et al. (1998; cf. Figure 3). For larger value of β too much protons are mixed into the transition zone, so that ^{14}N, rather than ^{13}C, forms.

An important remark concerns the mixing algorithm. Our tests show that when a diffusive scheme is adopted, as in many stellar evolution codes, the maximum resulting ^{13}C mass is too small to allow a sufficient s-process nucleosynthesis in the pocket (see Herwig 2000). On the other hand, it has been recently argued by Meakin & Arnett (2007) that the mixing occurring through the convective boundaries is not a diffusive process. As a matter of fact, ^{13}C pockets as large as those claimed by Gallino et al. (1998) can be obtained if the degree of mixing between two (mesh) points depends linearly on the inverse of their reciprocal distance, as in our time dependent mixing scheme (see Straniero et al. 2006).

We have calculated new models of low-mass stars by coupling the FRANEC stellar evolution code with a full network, from H to Bi. In such a way, we have been able to self-consistently derive the evolution and the nucleosynthesis along the whole AGB. The resulting compositions at the AGB tip for three models of solar metallicity are shown in Figure 4. The first ^{13}C pockets, those formed after the first two or three thermal-pulse episodes, are quite large (in mass). Later on, following the general shrinkage of the He-rich intershell, also the mass of the ^{13}C pocket decreases. So, the resulting heavy element distribution at the surface is mainly determined by the first few ^{13}C pockets. Note that, owing to the overlap of the various He convective zones, the imprint of these first bigger ^{13}C pockets is conserved up to the last dredge-up episode. At high metallicity and in stars with initial mass smaller than 3 $M_\odot$, the temperature in the He convective zone never attains values sufficiently large for the substantial activation of a second neutron burst driven by the ^{22}Ne$(\alpha, n)^{25}$Mg. Decreasing the metallicity, thermal pulses become stronger and generate larger temperatures, so that at $Z = 0.0001$ the additional contribution of the ^{22}Ne$(\alpha, n)^{25}$Mg to the neutron capture nucleosynthesis is rather important (Cristallo et al. 2009).

Let us conclude by noting that the theoretical scenario built up so far, after about fifty years of intense investigations, appears to be firmly supported by the observation of abundances in AGB stars undergoing the third dredge-up and belonging to different stellar populations.

Acknowledgments

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