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Models of AGB Stars and their Nucleosynthesis

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Abstract. The occurrence of recursive thermonuclear runaways makes the computation of AGB evolutionary sequences and the related nucleosynthesis a challenging task for stellar modelers. In the last 20 years many efforts have been made to improve the physical description of the interiors of these stars. Nevertheless, the majority of the extant nucleosynthesis results are based on post-process calculations, in which the evolution of the nuclear network and that of the stellar structure are treated separately and, hence, decoupled. In this paper, we review the latest attempts made to obtain more reliable nucleosynthesis calculations based on the physical processes expected to be at work in AGB stars, such as the mixing induced by convection and rotation.

1. Introduction

It is well known that low and intermediate mass stars ($M < 8\,M_\odot$) experience, after core He burning, an AGB phase. However, the evolution of the physical structure and the related nucleosynthesis differ from star to star, depending on the core mass (M_H, i.e., the internal H-exhausted zone), the envelope mass (M_{env}), and the original chemical composition. Figure 1 summarizes the main features of stars with different initial mass. Note that the precise values of the critical masses depend on the original chemical composition. Those in Fig. 1 refer to a solar composition (Z = 0.014, Y = 0.27). Stars with $M < 3\,M_\odot$ arrive on the AGB with quite similar core masses (~ 0.55 $M_\odot$), but their envelope mass depends on the initial mass and the pre-AGB mass loss. The Reimers formula ($\eta = 0.2 - 0.4$) represents quite well the mass-loss rate occurring during the first RGB. Then, at the end of the core He burning, single stars with initial mass as large as 0.8–0.9 $M_\odot$ should retain a sufficiently large envelope mass (larger than about 0.1 $M_\odot$, at least), so that they can enter the early-AGB phase and may experience some thermal pulses[1]. However, only TP-AGB stars whose residual envelope mass is larger than 0.3–0.4 $M_\odot$ can undergo the third dredge-up (TDU). In practice, there exists a critical value of the initial mass of about 1.2–1.3 $M_\odot$: below this limit, stars do not experience TDU episodes. We recall that the third dredge-up is a very important phenomenon, which determines the appearance at the stellar surface of the yields of the internal nucleosynthesis, such as He, C, N, F and heavy elements synthesized by

[1]In the case of an enhanced mass-loss rate, such as occurs in interacting binaries or in the case of envelope stripping caused by close encounters in crowded stellar systems, even more massive stars may lose most of the envelope and, in turn, may skip the AGB phase. Some hot sub-dwarfs could be the observational counterpart of these “AGB manqué" stars.

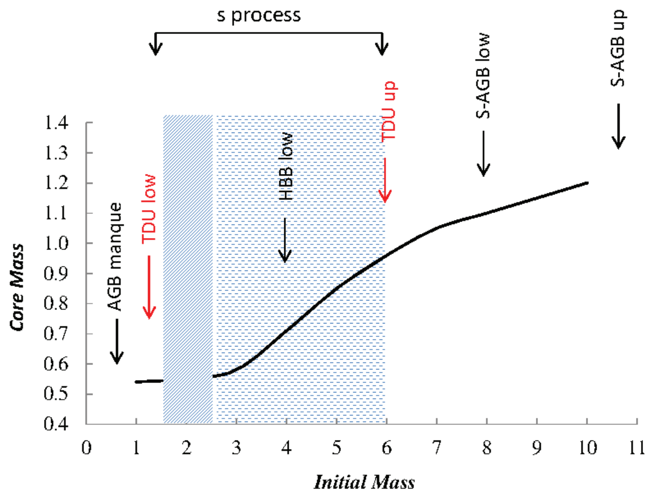

Figure 1. The mass of the H-exhausted core at the beginning of the AGB phase versus the initial mass. The arrows mark initial mass intervals for stars experiencing particular phenomena along the AGB phase, in particular: the lower and upper bounds for the occurrence of the TDU, the lower bound for stars undergoing HBB, and the minimum and maximum mass for the occurrence of degenerate carbon ignition (also stars experiencing a super-AGB phase). The smaller shaded area shows the region occupied by the stars that produce the main *s*-process component (elements with $A \geq 90$), while the larger shaded area is occupied by stars for which the *s*-process mainly occurs at high temperature, within the convective shells generated by thermal pulses.

slow neutron capture nucleosynthesis episodes (the *s*-process). Indeed, the occurrence of the third dredge-up is a necessary condition for the formation of the so-called ^{13}C pocket, which is the most important site of the *s*-process nucleosynthesis. In low-mass AGB stars ($1.5 \leq M/\mathrm{M}_\odot \leq 2.5$) the ^{13}C pockets are large enough to ensure the production of about half of all the stable isotopes with $A \geq 90$ that are found in nature (the so-called main component of the *s*-process). In this case, the neutron capture nucleosynthesis is powered by the $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ reaction (see next section). These stars are also the progenitors of the majority of the intrinsic C stars, i.e. stars close to the AGB tip showing C/O > 1. In addition to its importance for nucleosynthesis, the TDU limits the growth of the H-exhausted core and, in turn, affects many important physical parameters of the AGB. In stars with initial mass larger than $3\,\mathrm{M}_\odot$, the core mass at the beginning of the AGB becomes progressively larger[2]. The general rule is that the larger the core mass, the shorter the interpulse period and the smaller the He-rich intershell zone. As a result, less extreme physical conditions are attained at the He re-ignition, i.e., larger T and smaller ρ, so that weaker thermal pulses occur. Since the depth of the TDU depends on the strength of the preceding thermal pulse, smaller TDU episodes take place in the more massive AGB stars. In addition, a further phenomenon occurs in the more massive AGB stars that limits the TDU. It is the so called hot-TDU: when the

[2]In this mass range, indeed, the final core mass (M_H) essentially depends on the extension of the convective core during the main sequence phase.

convective envelope penetrates the H-exhausted core, it encounters hotter layers, until the H burning eventually restarts. The sudden release of nuclear energy produces an entropy barrier that induces a prompt stop of the TDU. Therefore, there also exists an upper mass limit for the occurrence of the TDU. Evaluation of the precise value is not straightforward, because of the difficulties concerning the treatment of time-dependent convection coupled to the thermonuclear burning. In our models we find that this limit is set at about 6 $M_\odot$. The same phenomenon also affects the extension of the ^{13}C pocket. In practice, in massive AGB stars the *s*-process nucleosynthesis is inhibited because of the too-small ^{13}C pocket. On the other hand, stars with $M > 3\,M_\odot$ develop rather high temperatures at the bottom of the convective zone generated by a thermal pulse (up to 350 MK). In these conditions a second neutron source, the ^{22}Ne$(\alpha, n)^{25}$Mg reaction, may be activated. However, due to the very different physical conditions, the yields of this alternative neutron burst are very different from those produced in the case of the radiative ^{13}C burning. In this case, the neutron density is rather high (up to 10^{13} neutrons/cm^3, compared to 10^7 neutrons/cm^3 in radiative ^{13}C burning), but the duration of a single neutron burst is significantly shorter (a few years, compared to 10^5 years). Therefore, the resulting neutron exposure, i.e., the time-integrated neutron flux, is smaller in the case of convective ^{22}Ne burning. This occurrence limits the *s*-process yields to the lightest elements of the main component, i.e. Rb, Y, Sr and Zr, whereas the heaviest elements, from Ba to Pb, are scarcely produced.

Finally, in stars with $M > 4\,M_\odot$ the bottom of the convective envelope is hot enough during the interpulse to trigger an efficient H burning. This phenomenon, called Hot Bottom Burning, implies an extra energy release, and it is an important source of nucleosynthesis of light isotopes. In the more massive AGB stars, for which $M_H \geq 1\,M_\odot$, the bottom temperature may become as large as 100 MK, so that the Ne-Na and Mg-Al cycles may be activated. Finally, stars with initial $M \geq 8\,M_\odot$ attain the conditions for C ignition in the core. Those with $8 \leq M/M_\odot \leq 11$ undergo a degenerate C ignition, which is characterized by quite a violent thermonuclear runaway. Later on, they form an O-Ne core and enter a super-AGB phase.

2. AGB Nucleosynthesis

Undoubtedly, the *s*-process is among the most striking features of the nucleosynthesis in AGB stars undergoing thermal pulses and third dredge-up. A few years after the first detection of radioactive ^{99}Tc in the atmospheres of S and C type red giants (Merrill 1952), it was realized that nucleosynthesis processes involving neutron captures must be at work in the deep interiors of these stars, since they are the only processes capable of circumventing the problem of the strong Coulomb barrier around nuclei heavier than Fe that prevents nuclear fusions (Burbidge et al. 1957). For a long time the most challenging question was the identification of a suitable source of neutrons (for a detailed historical review see Straniero et al. 2009). Finally, the standard paradigm of the *s*-process in low mass AGB stars was sketched by Straniero et al. (1995) and definitely settled in Gallino et al. (1998). In brief, the main neutron source is the ^{13}C$(\alpha$,n$)^{16}$O reaction, which is activated during the rather long interpulse period (up to 10^5 yr). At the time of the TDU, the convective envelope penetrates into the H-exhausted core, and then recedes. As a consequence, a zone characterized by a sharp H profile forms. Later on, when He burning ceases, this region of the star contracts and heats up, until H burning restarts. As a result of an incomplete CN cycle, a ^{13}C pocket forms that is

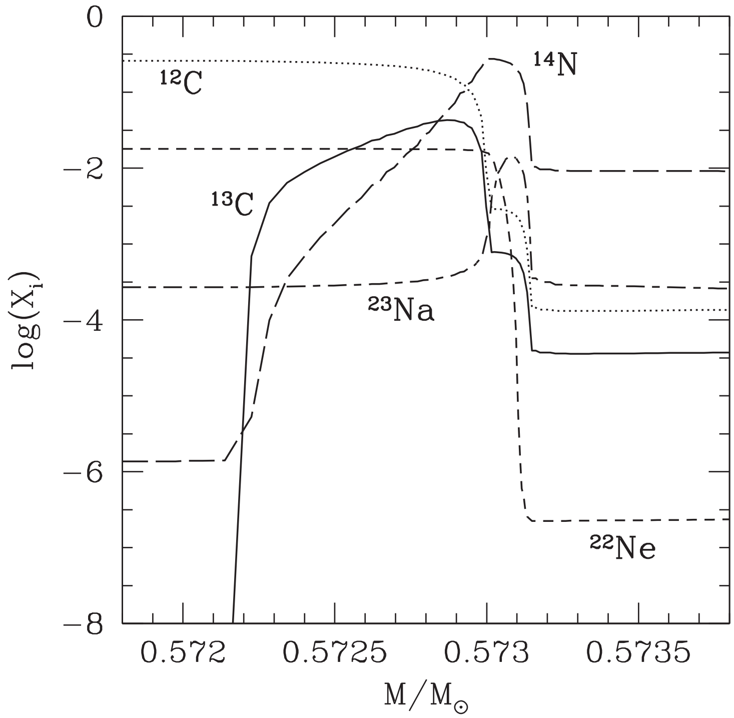

Figure 2. The ^{13}C pocket, partially overlapping with a more external ^{14}N pocket (see text). The plot shows the chemical profiles in the transition region between the He-rich intershell and the H-rich envelope, in a model of 2 $M_\odot$ (solar composition), during the third interpulse period and before the temperature becomes large enough to activate the $^{13}C(\alpha,n)^{16}O$ reaction (Straniero et al. 2006).

partially overlapped by a more external ^{14}N pocket (see Figure 2). Hence, when the temperature attains ~ 90 MK, the $^{13}C(\alpha,n)^{16}O$ reactions are activated and the *s*-process takes place. This scenario has been confirmed by several pieces of observational evidence, such as the analysis of the relative abundances of Rb and Sr, Yr and Zr in MS, S and C stars, which provides stringent constraints to the characteristics of the neutron capture nucleosynthesis (see, e.g., Lambert et al. 1995; Abia et al. 2001, and references therein). In particular, the neutron density should be quite low, namely between 10^6 and 10^8 neutrons/cm^3. As a consequence, the duration of the nucleosynthesis episode should be long enough to ensure a sufficiently large neutron exposure, as happens, indeed, in low-mass AGB stars.

The most challenging open problem of this scenario concerns the formation of the ^{13}C pocket. A suitable solution of this problem is strictly connected to understanding the physical processes causing mixing within the thin transition layer between the fully convective envelope and the fully radiative core. For instance, when the convective envelope penetrates the H-exhausted region, its innermost layers become unstable due to the formation of a sharp chemical discontinuity (Becker & Iben 1979; Frost & Lattanzio 1996; Straniero et al. 2006). Convective overshoot may induce some mixing into the underlying stable layer, so that the instability propagates inward on quite a short timescale, compared to the duration of a TDU episode. Later on, when the convec-

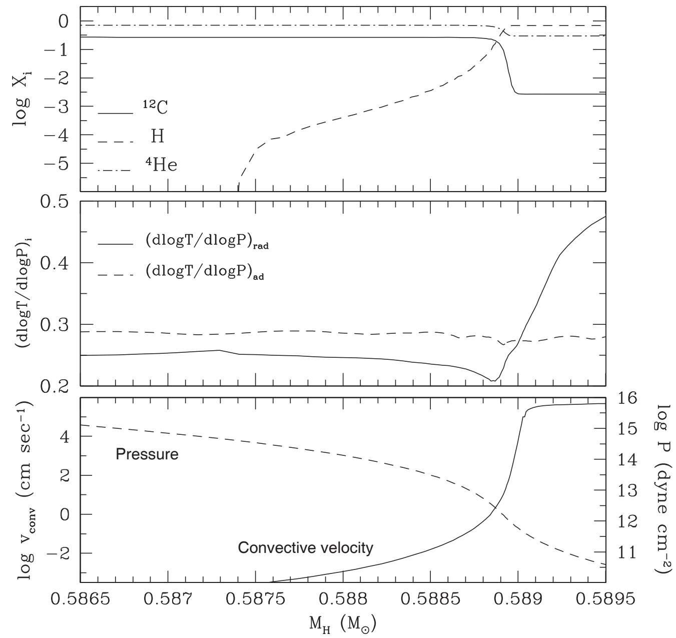

Figure 3. *Upper panel*: chemical profiles left by the TDU in the transition zone between the fully convective envelope and the fully radiative core. *Central panel*: radiative and adiabatic temperature gradients during the TDU. *Lower panel*: average convective velocity and pressure in the same zone (Straniero et al. 2006).

tive envelope recedes, it leaves a variable profile of H located just below the region where full mixing occurred. Then, the ^{13}C pocket will form where the H abundance is $0 < X_{\rm H} \leq 0.1$. Additional processes may also operate on a longer timescale, such as rotationally-induced mixing, magnetic buoyancy, or gravity waves. In practice, AGB nucleosynthesis is a complex interplay of several phenomena, among which convection and nuclear burning are the most important, but likely not the only ones. Interferences between different physical processes may be constructive or destructive, so that the resulting nucleosynthesis may be enhanced or suppressed. Therefore, although many attempts have been made to understand the efficiency of these processes, the existing stellar models do not yet provide a complete and self-consistent description of the ^{13}C pocket formation.

A nice picture of the difficulty of this problem is provided by the observation of the wet transition zone left by a sea wave on the shore[3]. The development of a reliable model to describe this zone is a hard task, obviously. As in the case of the TDU, it is the non-linearity of the equations describing the turbulent fluid motion that makes the solution a huge challenge for theoreticians.

[3] *bagnasciuga* is the untranslatable Italian word for this transition zone.

2.1. A Phenomenological Description of the Convective Overshoot

Time-dependent mixing algorithms require knowledge of the vertical velocity of the fluid (or the corresponding diffusion coefficient). In a convective layer, this velocity is usually computed by means of the mixing length theory (MLT) and depends on the local properties of the stellar plasma. According to the MLT, this velocity is proportional to the difference between the radiative and adiabatic temperature gradients ($\nabla_{\rm rad} - \nabla_{\rm ad}$). Since this quantity usually drops to 0 at a convective boundary, the average velocity also drops to 0. Nonetheless, turbulent eddies of different scales may penetrate the radiative stable layer, thus producing some extra-mixing. In many existing stellar evolution models, a unique prescription for this extra-mixing is often used; its extention is usually assumed to be a given fraction of the local pressure scale height, the same for all convective boundaries. However, the efficiency of the overshoot depends on the physical conditions at the convective border and in the adjacent stable zone (Singh et al. 1995). For instance, a particularly efficient overshoot is expected at the inner border of the convective envelope during a dredge-up episode. Note that in that case, because of the sharp chemical gradient, $\nabla_{\rm rad} - \nabla_{\rm ad} > 0$ at the convective border, so that the average vertical velocity of the turbulent eddies is $v_0 \gg 0$. Therefore, most of the turbulent eddies can penetrate into the stable zone, powering the formation of a chemically smooth transition zone between the fully convective envelope and the radiative core, where an incomplete mixing occurs. In order to estimate the efficiency of this extra-mixing we have to know how deep (on average) the penetration into the radiative stable core can be. In addition, the average vertical velocity in the envelope-core transition zone is needed. When the material accelerated by convection penetrates the stable zone, its velocity drops because of the buoyancy and viscosity. Let us assume that the deceleration is proportional to the square of the velocity, as happens to a body moving in a sufficiently dense fluid. With this simplification, we have:

$$\ddot{r} = \frac{dv}{dt} = -kv^2 \quad \rightarrow \quad \frac{1}{v} = kt + \frac{1}{v_0} \tag{1}$$

where k is a sort of viscosity coefficient and v_0 is the velocity at the convective border. Then, after a further integration, one gets:

$$v = \frac{dr}{dt} = \frac{1}{k}\frac{kv_0}{1 + kv_0 t} \quad \rightarrow \quad dr = \frac{1}{k}\frac{dW}{W} \quad \rightarrow \quad \delta r = \frac{1}{k}\ln(kv_0 t + 1) \tag{2}$$

where $W = kv_0 t + 1$ and $\delta r = r - r_0$. Finally, combining equations 1 and 2, we have:

$$v = v_0 \exp(-k\delta r) \tag{3}$$

Such an exponential decay of the average convective velocity, here obtained on the basis of a very simple argument, has been confirmed by more sophisticated hydrodynamical calculations (Singh et al. 1995; Freytag et al. 1996). For instance, in our AGB models we put $k = (\beta H_{\rm p})^{-1}$, where $H_{\rm p}$ is the pressure scale height, while β is a free parameter which determines the braking of the material that overflows into the stable radiative layer (Herwig et al. 1997; Straniero et al. 2006; Cristallo et al. 2009). In principle, the value of the braking parameter is not the same for different convective/radiative transition layers. As pointed out by Singh et al., a sizeable penetration into the stable zone may occur when the stability of the radiative layer outside the convective zone is weak. This is precisely the condition occurring below the convective envelope during

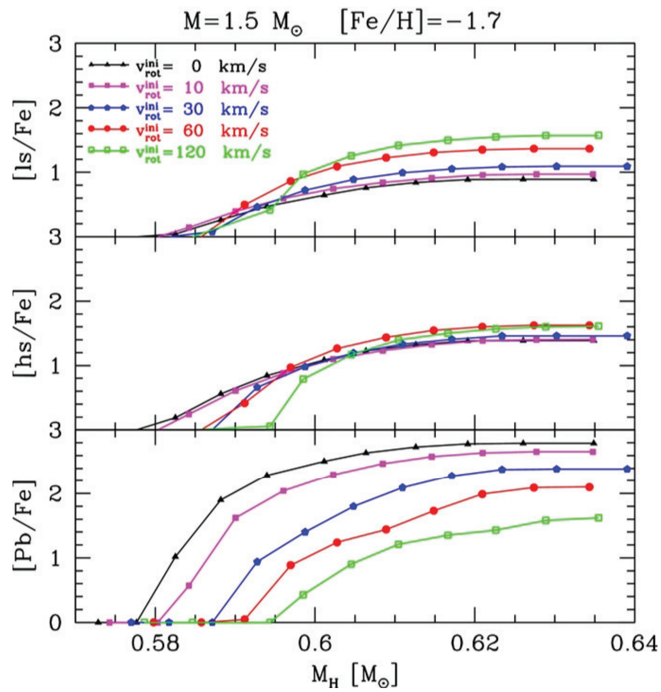

Figure 4. Evolution of light-*s* (Sr+Y+Zr), heavy-*s* (Ba+La+Ce+Nd) and Pb nuclei during the AGB of 1.5 $M_\odot$, [Fe/H] = –1.7, rotating models, under different assumptions for the initial (i.e. Zero Age Main Sequence) rotational velocity (Piersanti et al. 2013).

a TDU. In this case, indeed, the absolute value $|\nabla_{rad} - \nabla_{ad}|$ is small (~ 0.03) and nearly constant for more than 1 H_p (see central panel in Figure 3). As shown by Cristallo et al. (2009) (see also Cristallo et al. 2011), a variation of β at the inner border of the convective envelope has two major consequences. First, the larger the β the deeper the TDU. Since the amount of C dredged up depends on the TDU efficiency, a suitable calibration of β may be obtained by comparing theoretical and observed luminosity functions of carbon stars. Second, a maximum extension of the ^{13}C pocket is obtained for $\beta \sim 0.1$. Larger or lower values of β produce steeper H gradients in the transition zone between the fully convective and fully radiative regions and, in turn, smaller ^{13}C pockets. Therefore, the efficiency of *s*-process nucleosynthesis depends on β (Cristallo et al. 2009), so that a further constraint may be obtained by comparing the predicted heavy element composition to those observed in evolved AGB stars undergoing TDU. Both of these observational constraints indicate values of the β parameter close to 0.1 (Cristallo et al. 2011; Guandalini & Cristallo 2013).

2.2. Rotation and Mixing during the Interpulse Period

Recent rotational models of AGB stars have revealed the operation of two different kinds of instabilities within the He-rich intershell zone. Both are active during the rather long interpulse period. The first, a Goldreich-Schubert-Fricke instability takes place in the upper portion of the intershell, where a rather steep gradient of the rotational velocity is left by the receding convective envelope (Herwig et al. 2003; Siess et al.

2004; Piersanti et al. 2013). The consequent mixing partially overlaps the upper part of the newly formed ^{13}C pocket. Therefore, ^{13}C (the neutron source) is mixed with ^{14}N (the major neutron poison), thus reducing the efficiency of the whole *s*-process nucleosynthesis. The second is the Eddington-Sweet instability, which appears below the ^{13}C pocket (Piersanti et al. 2013). In this case, the innermost tail of the ^{13}C pocket stretches out, so that the same amount of ^{13}C is distributed over a larger zone containing more iron seeds. This occurrence affects the final distribution of the *s*-elements which is sensitive to the neutrons-to-seeds ratio: the production of the heavy-*s* nuclei (Pb, in particular) is hampered, while that of light-*s* elements (such as Sr, Y and Zr) is enhanced (see Figure 4). As a whole, rapid rotation may completely inhibit the *s*-process nucleosynthesis in AGB stars. Nevertheless, if there is just moderate rotation, a suitable amount of *s*-elements may be produced, but the resulting overall distribution is modified because of the lower neutrons-to-seeds ratio. A good picture of the additional mixing induced by rotation is that of a long and slow tidal wave, like those commonly observed on the French north coast.

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