AGB EVOLUTION WITH OVERSHOOT: HOT BOTTOM BURNING AND DREDGE UP

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ABSTRACT. We calculated models of massive AGB stars with a self-consistent coupling of time-dependent mixing and nuclear burning for 30 isotopes and 74 reactions. Overshoot with an exponentially declining velocity field was considered and applied during all stages of evolution and in all convective regions. Very efficient 3^{rd} dredge-up was found even overcompensating the growth of the hydrogen-exhausted core after a few thermal pulses. Hot bottom burning occurs for $M \geq 4\,\mathrm{M}_\odot$ within the sequences with overshoot. Carbon star formation in these more massive AGB stars is delayed or even prevented by hot bottom burning despite the very efficient dredge-up. With the simultaneous treatment of mixing and burning the formation of Li-rich AGB stars due to the Cameron-Fowler mechanism was followed. For a $6\,\mathrm{M}_\odot$ model the maximum Li abundance was found to be $\epsilon(^7\mathrm{Li}) \approx 4.4$.

1. Introduction

In recent stellar evolution calculations Herwig et al. (1997) have considered diffusive overshoot for all convective boundaries which leads to a considerable change in the models. This method provides for Asymptotic Giant Branch (AGB) stars a sufficient amount of dredge-up to form low-mass carbon stars as required from observations. Additionally it leads to the formation of ^{13}C as a neutron source to drive the s-process in these stars. More details are given in Herwig et al. (1999).

However the consequences for massive AGB stars, which suffer from hot bottom burning, remain to be investigated in detail. Hot bottom burning, i.e. the penetration of the convective envelope into the hydrogen burning shell, provides lithium-rich AGB stars and may delay or prevent the carbon star stage by turning ^{12}C into ^{13}C and ^{14}N. We have extended our computations of AGB stars with diffusive overshooting to hot bottom burning models including a self-consistent coupling of nucleosynthesis and mixing.

2. Computational details

We used the evolutionary code of Blöcker (1995). Nuclear burning was accounted for by a nuclear network covering 30 isotopes and 74 reactions up to carbon burning. We considered the opacities of Iglesias & Rogers (1996) supplemented with those of Alexander & Ferguson (1994) for the low temperature regime.

Convection was treated within the mixing length theory (Böhn-Vitense 1958) with a mixing-length parameter $\alpha = 1.7$. Mixing of chemical elements was treated by solving a diffusion equation. Overshoot was taken into account according to the prescription of Herwig et al. (1997) which is based on the hydrodynamical calculations of Freytag et al. (1996). Freytag et al. (1996) showed that mixing takes place well beyond the classical Schwarzschild border due to overshooting convective elements with an exponentially declining velocity field. In the overshoot region the corresponding diffusion coefficient is given by $D_{\rm os} = v_0 \cdot H_{\rm p} \cdot \exp \frac{-2z}{f \cdot H_{\rm p}}$ with v_0: velocity of the convective elements immediately before the Schwarzschild border; z: distance from the edge of the convective zone; f: the overshoot efficiency parameter. We used an efficiency parameter of $f = 0.016$ as appropriate to match the observed width of the main sequence. Diffusive overshooting was considered in all convective regions during the complete evolution.

Abundance changes have been treated self-consistently by coupling time-dependent mixing and nuclear burning of all chemical elements, i.e. by solving

$$\frac{{\rm d}X_i}{{\rm d}t} = \left(\frac{\partial X_i}{\partial t}\right)_{\rm nuc} + \frac{\partial}{\partial m}\left[(4\pi r^2 \rho)^2 D \frac{\partial X_i}{\partial m}\right]_{\rm mix}$$

The simultaneous treatment of burning and mixing is essential to follow, e.g. the ^{7}Li-production in luminous AGB stars via the Cameron-Fowler mechanism (Cameron & Fowler 1971, see also Sackmann & Boothroyd 1992). The self-consistent solution of time-dependent burning and mixing processes is, however, associated with a considerable increase of computing time due to the size of the problem (30 isotopes, $\sim$ 2000 mass shells). We calculated sequences for initial masses of $3{\rm M}_\odot$ to $6\,{\rm M}_\odot$ and $(X, Y) = (0.70, 0.28)$ from the pre-main sequence stage up to the AGB and through the thermal pulses. In order to disentangle the influence of mass loss from the one of overshoot we refer in this study only to sequences with small mass-loss rates (Reimers 1975, $\eta = 1.0$). Complete sequences will also consider stronger (and better suited) rates (cf. Blöcker 1995).

3. Thermal pulses and third dredge up

On the upper AGB the helium burning shell becomes recurrently unstable raising the thermal pulses (Schwarzschild & Härm 1965, Weigert 1966). During these instabilities the luminosity of the He shell increases rapidly for a short time of 100 yr to 10^6 to $10^8\,{\rm L}_\odot$. The huge amount of energy produced forces the development of a pulse-driven convection zone which mixes products of He burning, carbon and oxygen, into the intershell region. Because the H shell is pushed concomitantly into cooler domains H burning ceases temporarily allowing the envelope convection to proceed downwards after the pulse, to penetrate those intershell regions formerly enriched with carbon and to mix this material to the surface (3rd dredge up, see, e.g., Blöcker 1999 for a recent review). Overshoot leads to an enlargement of the pulse-driven convection zone and to enhanced mixing of core material from deep layers below the He shell to the intershell zone ("intershell dredge-up") and to a deepening of the envelope convection. If the determination of convective boundaries is solely based on the Schwarzschild criterion as in our case, dredge up can easily be obtained if some envelope overshoot is present to overcome the H/He discontinuity. The total amount of dredge up, however, depends mainly on the strength

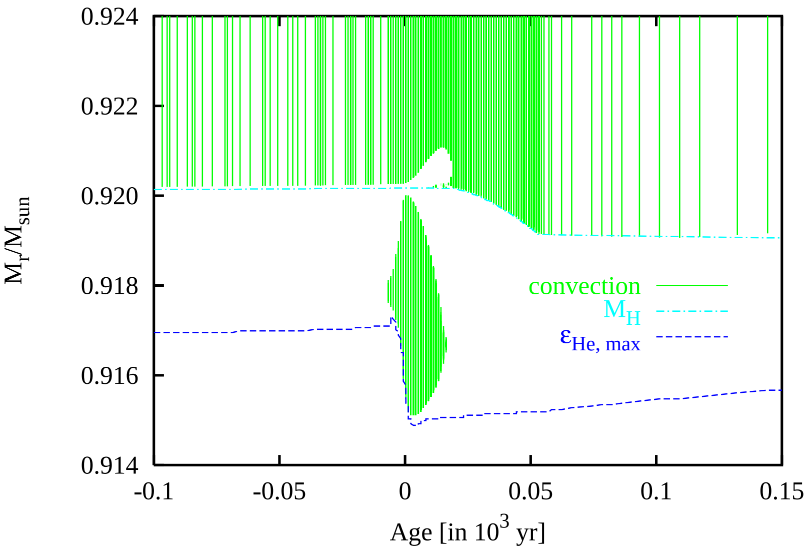

Fig. 1. Temporal evolution of the extension of convective regions for a $6\,M_\odot$ model during the second thermal pulse. The hatched regions refer to the bottom of envelope convection and to the pulse-driven convective zone of the He shell. The dashed-dotted line refers to the core mass M_H, and the dashed one to regions of maximum energy production $\varepsilon_{\rm He,max}$ in the He shell.

of the former intershell dredge-up (cf. Herwig et al. 1999). As in the case of low-mass stars intershell dredge-up leads to considerable changes of the intershell abundances. After intershell dredge-up the abundances (mass fractions) of He, C, O amount to (40,40,14) instead to (70,25,2) as in non-overshoot sequences.

Fig. 1 shows how the lower boundary of the envelope convection as well as the pulse-driven convection zone evolve during a pulse for a $6\,M_\odot$ model. The introduction of overshoot and its application to all convective boundaries provides $3^{\rm rd}$ dredge up even for low-mass AGB stars (Herwig et al. 1997, 1999) and we found very efficient dredge up for higher masses as well. With the dredge-up parameter λ being the ratio of material mixed up during the dredge up and the material burnt during two consecutive thermal pulses we find $\lambda > 1$ already during the very first pulses. Correspondingly, one observes a decrease of the mass of the hydrogen-exhausted core M_H (see Fig. 3).

Due to the overshoot we found high temperatures at the bottom of the pulse-driven convection zone. As demonstrated in Fig. 2 one obtains for a $3\,M_\odot$ sequence temperatures already close to $300 \cdot 10^6\,K$, the threshold temperature of the neutron source ^{22}Ne(α,n)^{25}Mg to operate. More massive models show even temperatures of $350 \cdot 10^6\,K$ and more after a few pulses. Thus, the *s*-process nucleosynthesis in these stars will be governed by both the ^{13}C(α,n)^{16}O and the ^{22}Ne(α,n)^{25}Mg neutron source.

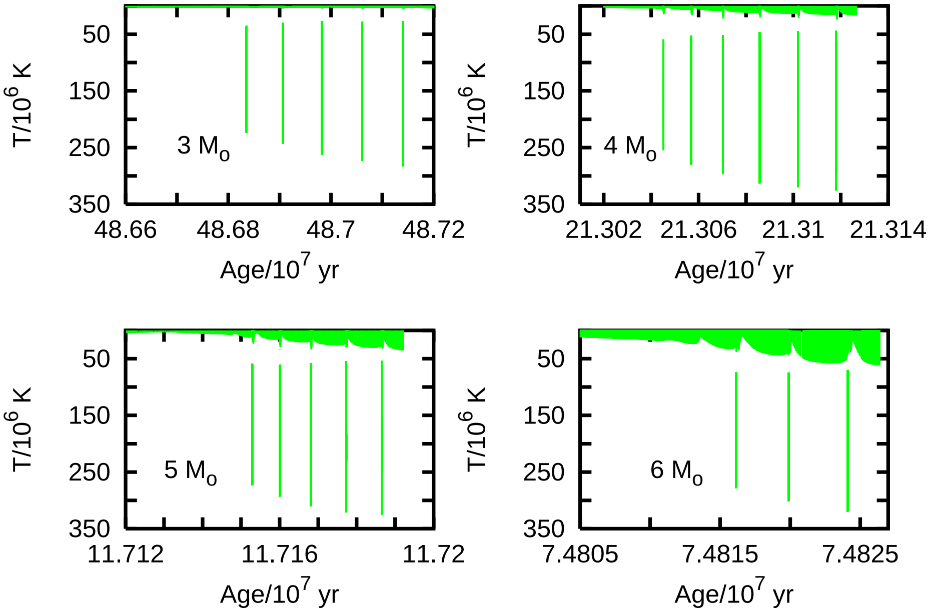

Fig. 2. Temperature vs. mass for convective regions for different initial masses. The hatched regions refer to the bottom of envelope convection and the "spikes" to the pulse-driven convective zone of the He shell.

4. Hot Bottom Burning

In more massive AGB stars ($M_{\rm initial} \gtrsim 4\,{\rm M}_\odot$) the convective envelope becomes so extended downwards that it can cut into the hydrogen burning shell during the interpulse phase (hot bottom burning (HBB) or envelope burning; Iben 1975, Scalo et al. 1975). Temperatures in excess of $50 \cdot 10^6$ K (see Fig. 4) are reached at the base of the convective envelope and material burnt there is immediately mixed to the surface. HBB models do not obey Paczynski's (1970) classical core-mass luminosity relation but, instead, evolve rapidly to very high luminosities (Blöcker & Schönberner 1991). Due to CNO cycling of the envelope ^{12}C can be transformed into ^{13}C and ^{14}N. Consequently, a low ^{12}C/^{13}C ratio is a typical signature for HBB which can prevent AGB stars from becoming carbon stars (Iben 1975; Renzini & Voli 1981; Boothroyd et al. 1993, Frost et al. 1998).

The evolution of different CNO isotopic ratios at the surface of our $5\,{\rm M}_\odot$ sequence is shown in the lower panel of Fig. 3. The ^{12}C/^{13}C ratio reaches its equilibrium value (≈ 3) after the first pulses and ^{14}N/^{12}C starts to increase whereas ^{12}C/^{16}O decreases. Although dredge-up is very effective leading even to a core-mass decrease, HBB is so efficient that it prevents or delays the star to become a carbon star.

The evolution of the surface abundances depends on the competition between HBB and dredge up. Both effects depend on the envelope mass, i.e. on mass loss. Consequently, the C/O ratio reached at the end of the AGB evolution depends crucially on the question which process will shut down first. The critical minimum enevelope mass for efficient

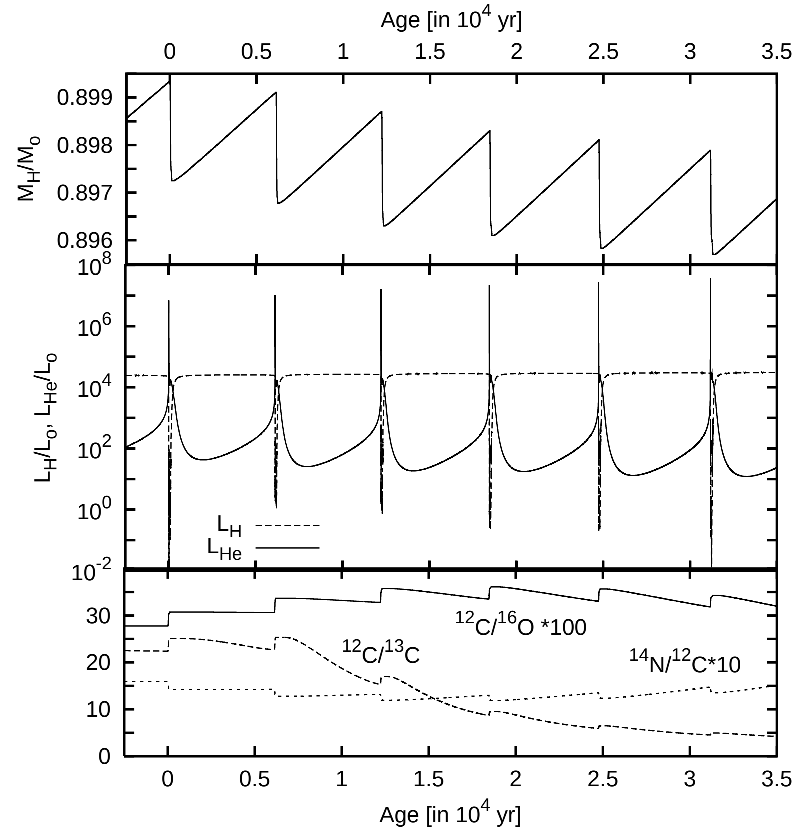

Fig. 3. Temporal evolution of the core mass $M_{\rm H}$, the shell luminosities $L_{\rm H}$ and $L_{\rm He}$, and surface CNO isotopic ratios (from top to bottom) for a $5\,{\rm M}_\odot$ sequence.

HBB appears to be larger than the one necessary for dredge up (Frost et al. 1998), and it depends on the remaining dredge-up efficiency if finally carbon stars can be formed. Our calculations show that dredge up even operates during the post-AGB stage if overshoot is considered with important conclusions for the formation of hydrogen-deficient stars.

Another direct consequence of HBB is the formation of lithium-rich stars (Scalo et al. 1975) via the Cameron & Fowler (1971) mechanism: The timescale of the β-decay of ^{7}Be which is produced at the bottom of the envelope convection is comparable to the convective timescale. Therefore, before ^{7}Be is burnt in the lower part of the envelope it can be mixed up to cooler layers where it decays to produce ^{7}Li which, in turn, is then convected to the surface. This mechanism is effective for temperatures between 30 and $80 \cdot 10^6\,$K at the bottom of the envelope. The production of Li-rich AGB stars can only be followed with a simultaneous treatment of mixing and burning. Otherwise, ^{7}Be would be burnt at the bottom of the envelope before it can be mixed up.

Since the luminosity is a unique function of the base temperature and Li is only produced in a certain temperature range, Li-rich stars are only found between $M_{\rm bol} \approx$ -6 to -7

(Sackmann & Boothroyd 1992) in good agreement with observations of the Magellanic Clouds (Smith & Lambert 1990, Plez et al. 1993).

On the other hand, the majority of Li-rich galactic AGB stars are observed at much lower luminosities, $M_{\mathrm{bol}} \approx -3.5$ to -6 (Abia & Isern 1997). They are, however, carbon stars. Since ^{7}Li enrichment requires $T_{\mathrm{bottom}} \gtrsim 30 \cdot 10^{6}\,\mathrm{K}$ whereas ^{12}C is efficiently destroyed via CNO cycling for $T_{\mathrm{bottom}} \gtrsim 70 \cdot 10^{6}$ K one finds in standard evolution calculations only a narrow mass, age and brightness range where AGB stars should be both lithium and carbon rich indicating that possibly additional mixing processes operate in these stars (Abia & Isern 1997).

Recently, Ventura et al. (1999) calculated AGB models for the LMC with $M \leq 4\,\mathrm{M}_{\odot}$ considering overshoot in a similar manner as Herwig et al. (1997). They found Li-rich carbon stars only for $M = 3.5$ and $3.8\,\mathrm{M}_{\odot}$, i.e. for the upper part of the observed luminosity range. Our $4\,\mathrm{M}_{\odot}$ model ($Z = 0.02$) becomes a carbon star after 10 thermal pulses due to very efficient dredge up and can be expected to become lithium rich during the further course of evolution due to the sufficient increase of envelope base-temperatures. The $3\,\mathrm{M}_{\odot}$ model becomes a carbon star after a couple of thermal pulses as well but seems to miss the Li-rich stage. These findings are in line with those of Ventura et al. (1999). Thus, overshoot alone appears not to be able to explain galactic Li-rich carbon for the whole brightness range observed.

Fig. 5 illustrates the considerable ^{7}Li enrichment during the first thermal pulses for the $6\,\mathrm{M}_{\odot}$ sequence. Within the first 3 pulses the Li abundance increases by more than 5 orders of magnitude to reach almost 10 times the main sequence value. The maximum lithium abundance is $\epsilon(^{7}\mathrm{Li}) = \log\left[n(^{7}\mathrm{Li})/n(\mathrm{H})\right] + 12 \approx 4.4$ in agreement with the results of Sackmann & Boothroyd (1992).

Mazzitelli et al. (1999) calculated lithium production in AGB stars with application of overshoot to all convective regions as well. The overshoot treatment is comparable to the method of Herwig et al. (1997) but convection is dealt with the Canuto & Mazzitelli (1992) prescription. They obtained a similar evolution of lithium enrichment and base temperatures but found for a solar metallicity $6\,\mathrm{M}_{\odot}$ model a complete penetration of the hydrogen burning shell by the convective envelope resulting in a lack of helium accumulation in the intershell region and corresponding prevention of thermal pulses. A corresponding quenching of thermal pulses was not found for the present $6\,\mathrm{M}_{\odot}$ sequence (see Fig. 5).

5. Conclusions

We calculated models of massive AGB stars (solar metallicity) with a self-consistent coupling of time-dependent mixing and nuclear burning for 30 isotopes and 74 reactions. Treating exponential overshoot (Freytag et al. 1996) as in Herwig et al. (1997) and applying it to all convective regions we find very efficient 3$^{\mathrm{rd}}$ dredge-up with $\lambda > 1$ after a few thermal pulses. Overshoot leads to intershell dredge-up and provides considerably changes of the intershell abundances strongly enriched in carbon and oxygen, i.e. [He,C,O]=[40,40,14] by mass. These intershell abundances determine the strength of the third dredge up, whereas envelope overshoot is mainly required to penetrate the H/He discontinuity. Temperatures at the bottom of the flash-driven convection zone of

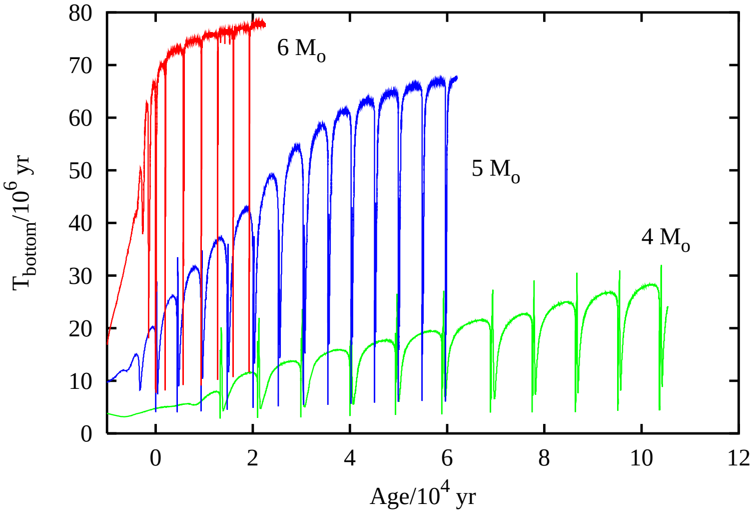

Fig. 4. Temperature at the base of the convective envelope for models with initial masses of 4, 5 and 6 M$_\odot$ The strong increase of $T_{\rm bottom}$ indicates the efficiency of HBB. $t = 0$ refers to the $L_{\rm He}$ maximum of the first thermal pulse.

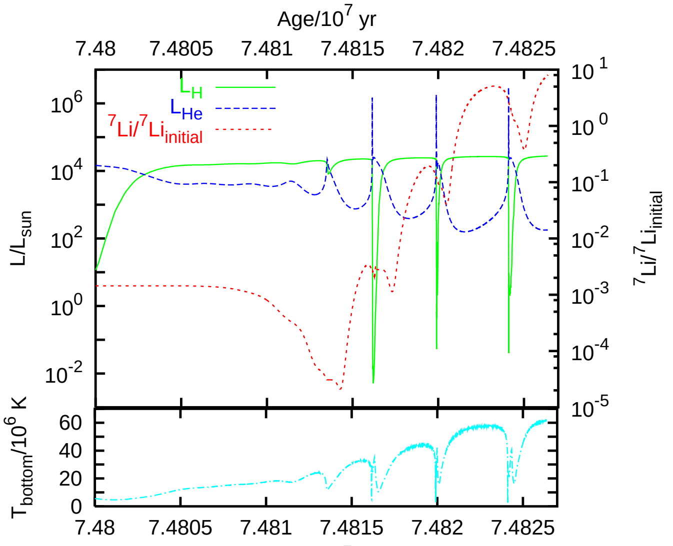

Fig. 5. Upper panel: Evolution of the shell luminosities $L_{\rm H}$ and $L_{\rm He}$, and of the surface abundance of ^{7}Li with respect to its initial value ($^7{\rm Li}_{\rm initial} = 9.35 \cdot 10^{-9}$) during the first thermal pulses of the $M = 6{\rm M}_\odot$ sequence. Lower panel: Corresponding evolution of the temperature at the bottom of the envelope convection.

the helium burning shell are in excess of $300 \cdot 10^6$ K after a few pulses activating the ^{22}Ne(α,n)^{25}Mg reaction for *s*-process nucleosynthesis.

Hot bottom burning occurs for $M \geq 4\,\mathrm{M}_\odot$ within our sequences with overshoot. Only the $4\,\mathrm{M}_\odot$ model becomes a carbon star whereas carbon star formation in more massive AGB stars is delayed or even prevented by hot bottom burning despite of the very efficient dredge-up. With the simultaneous treatment of mixing and burning the formation of Li-rich AGB stars due to the Cameron-Fowler mechanism was studied. Already the $4\,\mathrm{M}_\odot$ model becomes lithium-rich leading to the formation of a lithium-rich carbon star. For $M \geq 6\,\mathrm{M}_\odot$ the maximum Li abundance was found to be $\epsilon(^7\mathrm{Li}) \approx 4.4$.

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