The role of convective boundaries

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Abstract. We investigate the influence of convective overshoot on stellar evolution models of the thermal pulse AGB phase with $M_{\rm ZAMS} = 3{\rm M}_\odot$. An exponential diffusive overshoot algorithm is applied to all convective boundaries during all evolutionary stages.

We demonstrate that overshooting at the bottom of the pulse-driven convective zone, which forms in the intershell during the He-shell flash, leads to more efficient third dredge-up. Some overshoot at the bottom of the convective envelope removes the He-H discontinuity, which would otherwise prohibit the occurrence of the third dredge-up for this stellar mass. However, no correlation between the amount of envelope overshoot and the efficiency of the third dredge-up has been found.

Increasingly efficient third dredge-up eventually leads to a carbon star model. Due to the partial mixing efficiency in the overshoot region a ^{13}C-pocket can form after the third dredge-up event which may be crucial for n-capture nucleosynthesis.

1. Introduction

Current stellar evolutionary models of the AGB stage fail to reproduce a number of observationally based constraints. The observed carbon star luminosity function requires that the third dredge-up in AGB stars occurs efficiently at core masses of about $M_{\rm H} = 0.6{\rm M}_\odot$ (Groenewegen et al 1995, Marigo et al 1996).

For the explanation of s-process elements on the surface of AGB stars, dredge-up is an important prerequisite as well. Obviously, dredge-up enables the transport of processed material to the surface. But dredge-up is also needed in order to establish a region in the star where the H-rich convective envelope has immediate contact with the ^{12}C-rich intershell region. Additionally to sufficient dredge-up a mechanism must be identified to ingest protons into the intershell region in order to produce the neutron source ^{13}C via the reaction chain $^{12}{\rm C}({\rm p},\gamma)^{13}{\rm N}(e^{+}\nu)^{13}{\rm C}$ (Gallino et al 1998).

A certain class of post-AGB stars (about 20% of all central stars of planetary nebulae) show a hydrogen – deficient surface composition. The evolutionary origin of the typical abundance pattern of these stars [e.g. (He/C/O)=(33/50/17) in mass fractions for the PG1159 stars, Werner et al (1998)] are not well understood. One possible evolutionary scenario establishes a link between these surface abundances with the intershell abundance of the AGB stars (Iben & McDonald 1995). Current models, however, typically predict an abundance pattern like (^{4}He/^{12}C/^{16}O)=(70/26/1) for the intershell region.

In Sec. 2. we will describe the motivation and method of overshooting which we have applied to stellar evolution models of AGB stars. In Sec. 3. we focus on the effect of overshooting of the pulse-driven convective zone, which evolves in the intershell during the He-flash, on the intershell abundance. We will also discuss the role of overshooting at the bottom of the envelope convection zone for the third dredge-up. This will then lead to the presentation of the ^{13}C-pocket which also results from the overshooting treatment (Sec. 4.).

2. Overshooting with decreasing mixing efficiency

Overshooting is the mixing of material beyond the boundary of convection. The impact of overshooting has been studied for different stellar conditions in order to address various problems in stellar evolution models. For example, Shaviv & Salpeter (1973) and Maeder (1975) have studied the general properties of overshooting at the boundary of a convective core. The effect of overshooting at the bottom of the convective envelope has been studied by Alongi et al (1991) for red giant branch stars and by Iben (1976) for AGB stars.

Mixing due to overshoot has often been treated by the formal extension of the instantaneously mixed convective region (Schaller et al 1992). However, hydrodynamic simulations (Freytag et al 1996) of the surface convection zone of A-stars and white dwarfs show prominent convective rolls and downdrafts which extend beyond the boundary of convection and lead to a partial mixing of this region. The exponential decay of the turbulent velocity field and the diffusive character of the associated mixing are common features of this overshoot. These results have motivated the ansatz for an exponentially declining diffusion coefficient for the overshoot region in order to describe the mixing beyond the convective boundary (Herwig et al 1997). Further on, we assume that the exponential diffusive description of overshoot is applicable to the deep stellar interior. For this region we have scaled the exponential coefficient f by fitting the main sequence width. We then assumed that the resulting exponential coefficient of $f = 0.016$ can serve as an approximation for the convective boundaries encountered in AGB stellar models.

This method of *exponential diffusive overshoot* has been applied to all convective boundaries during the AGB evolution (and before). This includes the pulse driven convective zone in the intershell layer which results from the huge energy release during the He-shell flash.

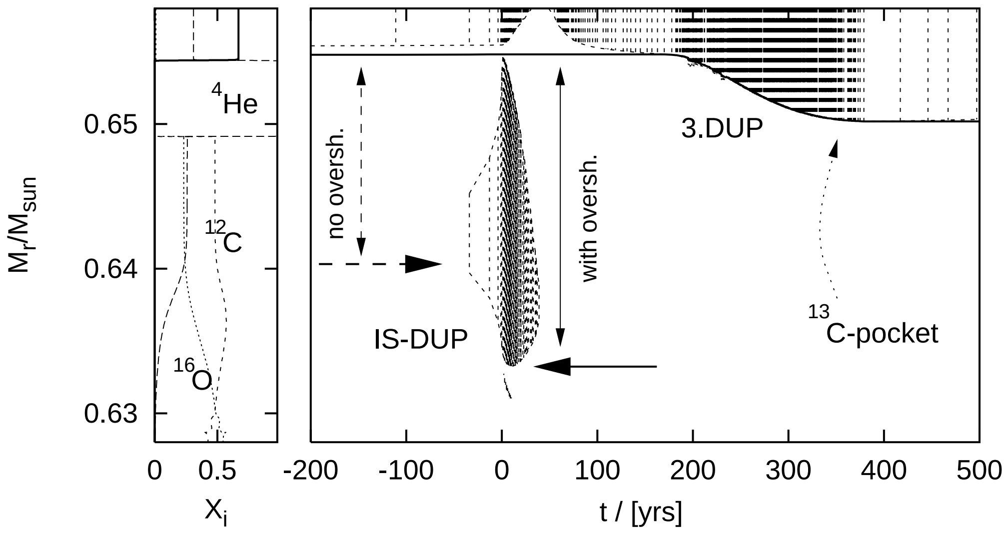

Figure 1. Isotopic abundance profiles of ^{4}He, ^{12}C and ^{16}O at the end of the interpulse phase (left) and the evolution of convective regions during a thermal pulse (at $t = 0$yr) including the third dredge-up (main panel) at the 9$^{\rm th}$ TP of a $M_{\rm ZAMS} = 3{\rm M}_{\odot}$ sequence. In the main panel the regions covered with vertical dashed lines are convectively unstable (convective envelope at the top and the pulse-driven convective zone in the center of the figure). The density of these lines indicate the variation of the time resolution. The dashed arrows (labeled no oversh.) indicate the extend that a pulse-driven convective zone during a TP with this core mass would have without application of overshoot to this convective region. Label IS-DUP:*intershell dredge-up*.

3. The dredge-up in the pulse-driven convective zone and the third dredge-up

While overshoot at the top boundary of the pulse-driven convective zone has no noticeable effect, mixing beyond the bottom boundary leads to a decrease of the ^{4}He abundance in the intershell. At the same time the intershell region is enriched with ^{12}C and ^{16}O. This change of composition leads to an increase of opacity and therefore the radiative gradient $\nabla_{\rm rad}$ (which is proportional to the opacity) is lifted with respect to the adiabatic gradient $\nabla_{\rm ad}$, and the further downwards extension of the pulse-driven convective zone is supported. This process drives an even deeper penetration of the pulse-driven convective zone into the core region. In Fig. 1 the left panel shows the abundance profiles in the mass range of the two burning shells shortly before the flash occurs, which is shown in the main panel. The region between the mass coordinates $M_{\rm r} \approx 0.64{\rm M}_{\odot}$ and $\approx 0.65{\rm M}_{\odot}$ shows the already altered intershell abundances (compared to standard calculations) formed during previous thermal pulses. The almost pure He layer above $M_{\rm r} \approx 0.65{\rm M}_{\odot}$ results from H-shell burning during the previous interpulse

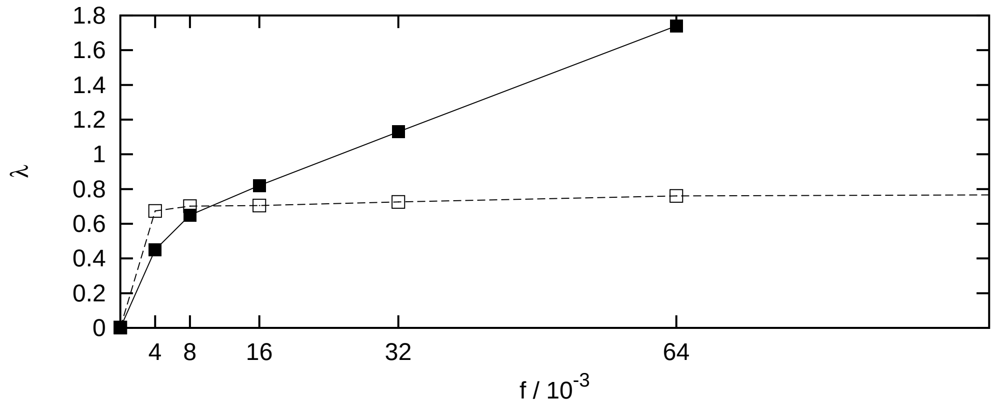

Figure 2. The open symbols (dashed line) show λ [λ = (core mass decrease by dredge-up) / (core mass growth by hydrogen burning)] for a series of test sequences started at $t \approx +100$yr after the $8^{\rm th}$ TP flash peak (when the pulse-driven convective zone has already disappeared), with different values of f (during all previous evolution $f = 0.016$ has been used). Each test sequence has been evolved through the next pulse with the f value indicated. The filled squares (solid line) show λ after this next pulse. The difference is that here also the pulse-driven convective zone has been computed with the changed f value.

phase. Below $\approx 0.64 M_\odot$ the ^{4}He abundance drops continuously according to the preceding He-shell burning. The pulse-driven convective zone of a TP computed without overshoot would not extend into this He-poor region as can be seen from the dashed arrow in the main panel of Fig. 1. In contrast to that the pulse-driven convective zone actually shown in the main panel is computed with overshoot and does extend much deeper into the core. It covers a mass fraction which is larger by about a factor of 1.5 compared to the pulse-driven convective zone without overshoot. One might call this process *intershell dredge-up* (IS-DUP).

If overshooting at the bottom of the pulse-driven convective zone is considered, the intershell abundance evolves with pulse number. While the ^{4}He abundance decreases steeply over the first pulses at the expense of ^{12}C, the ^{16}O abundance increases steadily. After about a dozen pulses the ^{4}He abundance has recovered from a relative minimum (corresponding to a relative maximum of ^{12}C) and all three abundances level at about (He/C/O)=(40/40/16). These changed intershell abundances (compared to standard models) may eventually contribute to a better understanding of the above mentioned abundance patterns of H-deficient post-AGB stars.

After the pulse-driven convective zone has disappeared IS-DUP has led to an intershell abundance which contains less ^{4}He compared to models without overshoot. Then, following the arguments given in the previous section, the efficiency of the third dredge-up is enhanced. This can be seen from Fig. 2. If a larger overshoot efficiency is applied to the pulse-driven convective zone (filled symbols) less ^{4}He is present in the intershell region after the TP and the third dredge-up is more efficient. Thus, we find that the application of overhoot to

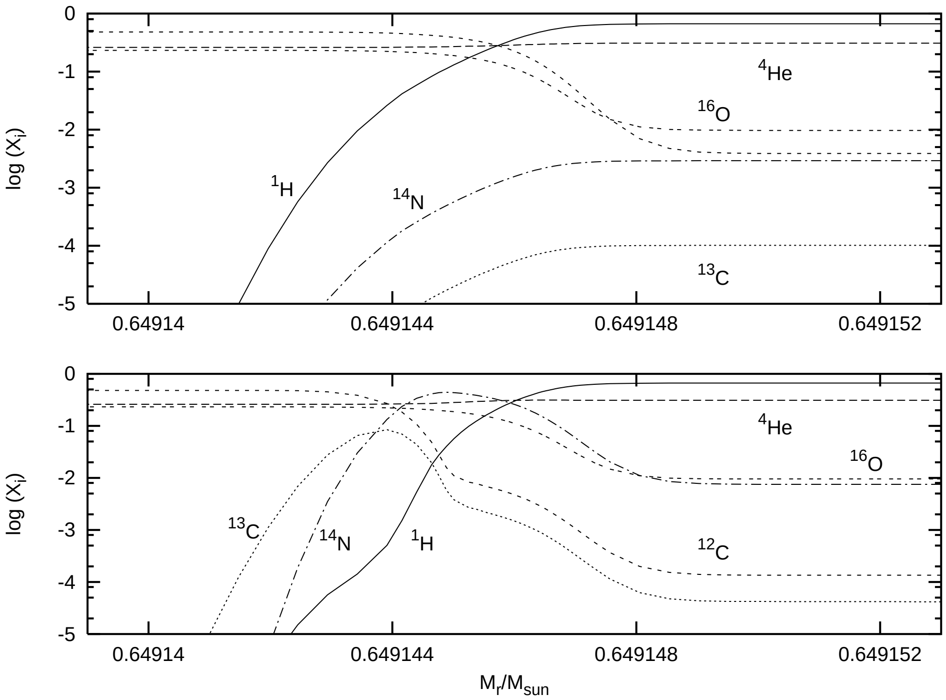

Figure 3. After the 8$^{\rm th}$ TP of a $M_{\rm ZAMS} = 3{\rm M}_\odot$ sequence: Isotopic abundance profiles at the interface of ^{12}C-rich intershell and H-rich envelope shortly after the end of the third dredge-up (top) and about 1800yr later when the ^{13}C-pocket has developed (bottom).

the pulse-driven convective zone during the He-shell flash increases the amount of third dredge-up occuring immediately after the TP.

But what is the role of overshoot at the bottom of the convective envelope? The open symbols in Fig. 2 each represent the dredge-up efficiency λ when f has been changed *after* the pulse-driven convective zone has disappeared. This means that all these dredge-up events occur with identical intershell abundance (the same overshoot has been applied to the previous pulse-driven convective zone). Only the efficiency of the overshoot at the bottom of the convective envelope is different. One can see that the amount of overshoot at this convective boundary is not related to the dredge-up efficiency. The only effect of this overshoot is the removal of the H-He discontinuity which would otherwise prohibit the third dredge-up in our models ($\lambda = 0$ for $f = 0$ in Fig. 2). We conclude that some non-zero overshoot at the bottom of the convective envelope is necessary in our models to make the third dredge-up at all possible (However, Straniero et al (1997) did find the third dredge-up for similar core masses without invocation of overshoot.) while overshoot at the bottom of the pulse-driven convective zone has an effect on the efficiency of the third dredge-up. Our model sequence shows the third dredge-up with increasing efficiency from the third thermal pulse on until ($\lambda > 1$). A carbon model star is found after the 12^{th} TP.

Finally we note, that the efficient dredge-up leads to deviations from the linear core mass - luminosity relation originally described by Paczyński (1970). The deviations occur at lower core masses than those associated with hot bottom burning. They can be understood by the analysis of homology relations as described by Herwig et al (1998).

4. The ^{13}C-pocket

The overshoot effects described so far are possibly not strongly depending on the overshoot description. However, *partial* mixing beyond the bottom of the envelope convection becomes crucial when the third dredge-up comes to an end. Then the bottom of the H-rich envelope is immediately neighbored by the ^{12}C-rich intershell region and due to the exponential diffusive overshoot a thin layer forms where protons and ^{12}C coexist (Fig. 3, top panel). When the temperatures rise in this region due to resuming contraction after the TP a ^{13}C-pocket (^{13}C-rich layer) is formed (Fig. 3, bottom panel). It typically contains about $3 \cdot 10^{-7} \mathrm{M}_{\odot}$ of ^{13}C. It may, in the further course of the pulse, serve as the neutron source for the formation of heavy elements. While the qualitative modeling of such a pocket is quite encouraging the ^{13}C formation must be investigated more quantitatively in the future.

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