Overshoot in Giant Stars

F. Herwig [1] and T. Blöcker[2]

[1]Institut für Physik, Astrophysik, Universität Potsdam, Germany
fherwig@astro.physik.uni-potsdam.de
[2]Max-Planck-Institut für Radioastronomie, Bonn, Germany
bloecker@speckle.mpifr-bonn.mpg.de

Abstract: The concept of overshoot has already been considered for numerous cases in stellar evolution calculations. We explore the consequences of overshoot at the convection zone which forms during the He-flash (thermal pulse) in AGB stars. We find dramatic changes for the abundances within the intershell region as well as for the mechanism of the 3$^{\rm rd}$ dredge-up. That means that both the predicted evolution of structural quantities as well as the chemical evolution at the surface will be different, if overshoot is considered. We also present evidence for the presence of overshoot during the He-flash from detailed model calculations of the post-AGB phase and the comparison with observations. The new evolutionary models show that a very late thermal pulse during the post-AGB evolution can bring the intershell material up to the surface with minimal modification due to convective H-burning. The good agreement of the surface abundances of these models with observed surface abundances of H-deficient post-AGB stars is interpreted as a strong support for the presence of overshoot during the thermal pulses of AGB stars.

1 Introduction

The observation of metal-poor stars in globular clusters and field stars has revealed many well-defined correlations of abundance ratios. If these results are combined with theoretical predictions for nucleosynthetic production site the chemical evolution of stellar populations can be reconstructed. Among the nucleosynthetic production sites to be considered are the asymptotic giant branch (AGB) stars which are potentially efficient producers of carbon, nitrogen and s-process elements (Jehin et al., 1999). In contrast to the contribution from massive stars and supernovae, which can be identified down to the lowest [Fe/H] ratios, AGB stars contribute with some delay to the enrichment of the ISM.

AGB stars are characterized by an increasingly degenerate C/O core and two shells of nucleosynthetic processing: the helium burning shell and the hydrogen burning shell (Iben and Renzini, 1983). The He-shell can become thermally unstable which leads to the recurrent thermonuclear run-away of He-burning in the shell, the thermal pulses (TP). During the TP the region between the hydrogen and the helium shell, the intershell region, becomes convectively unstable due to the huge nuclear energy production of the He-shell (Fig. 1) (Blöcker, 1999).

The predictions of yields, chemical enrichment and surface abundances as well as stellar parameters, like luminosity, are sensitively dependent on the overshoot phenomenon. In the next section we will review the most important changes introduced to the AGB models if overshoot is considered. Section 3 will discuss new stellar evolution models of hydrogen-deficient post-AGB stars and their

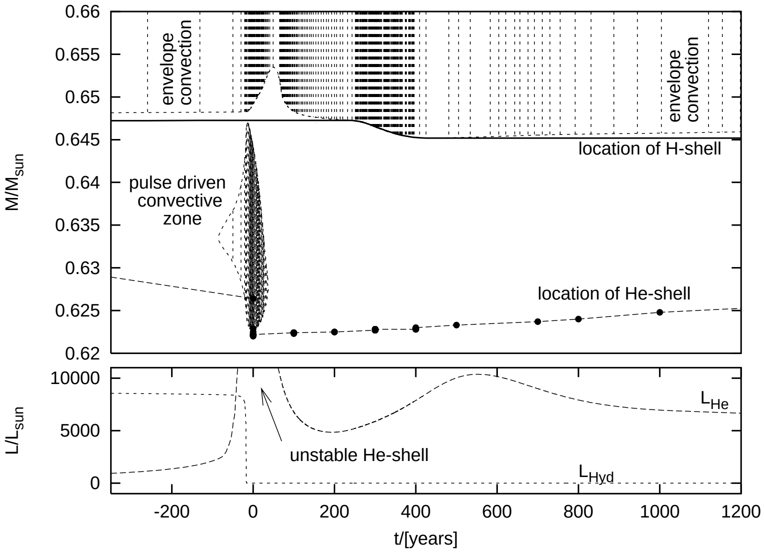


Figure 1: During a thermal pulse. **Top panel:** Convective regions are indicated by vertical lines, which are spaced according to the model density. Around $t = 0\,\mathrm{yr}$ the He-flash convection zone homogenizes the intershell region from the top of the C/O core almost up to the mass coordinate of the H-free core. In the intershell region the ashes of the H-shell burning accumulate during the previous quiescent interpulse phase. This material consists mainly of helium ($\simeq 98\%$ by mass) and all CNO material has been transformed into ^{14}N. About $350\,\mathrm{yr}$ after the TP the envelope convection reaches into the intershell layer and material previously partially processed by helium burning is dredged-up to the surface. **Lower panel:** Luminosity contributions of helium and hydrogen burning. At $t = 0\,\mathrm{yr}$ the peak He-luminosity has been reached. Hydrogen burning has ceased because the layers at which hydrogen is still present are geometrically lifted due to the expansion work from the underlying unstable helium shell. The TP itself has a duration of the order of $100\,\mathrm{yr}$.

observational counterparts. We argue that this class of stars can only be understood if overshoot in AGB stars is indeed operating.

2 Nucleosynthesis and mixing in AGB stars with overshoot

Stellar AGB models with overshoot are different from models without overshoot with respect to

- the formation of a ^{13}C pocket which is a crucial ingredient of the concept of ^{13}C being the dominant neutron source of the main solar s-process component produced in low-mass AGB stars,
- the occurrence and efficiency of the third dredge-up (Herwig et al., 1997; Herwig et al., 1999b),
- the composition in the intershell and thereby also of the ejecta and
- the structural evolution (Herwig et al., 1998).

2.1 The neutron source for the s-process

At the end of the third dredge-up phase the hydrogen-rich convective envelope and the carbon-rich intershell region have direct contact. A tiny region can form were protons and ^{12}C coexist. It has

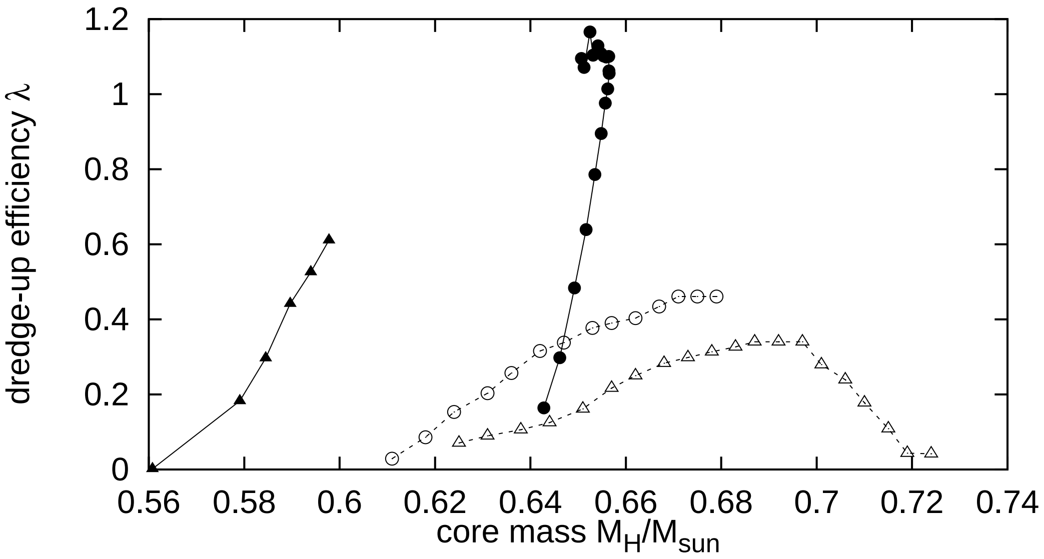


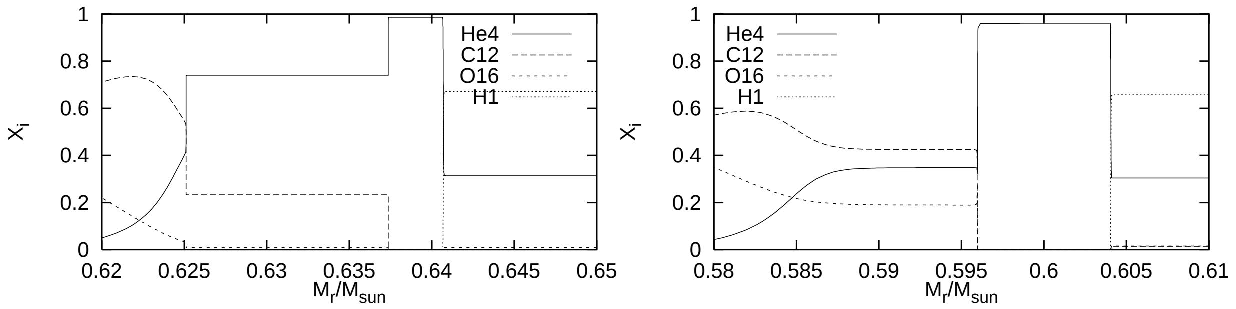
Figure 2: The dredge-up efficiency $\lambda = \Delta M_{\mathrm{DUP}}/\Delta M\mathrm{H}$ as a function of the core mass for models with overshoot (full symbols, this work) and without overshoot (open symbols) by Straniero et al. (1997). Circles: M_{ZAMS}=3 $\mathrm{M}_{\odot}$, full triangles: $2\,\mathrm{M}_{\odot}$, open triangles: $1.5\,\mathrm{M}_{\odot}$. For the $3\,\mathrm{M}_{\odot}$ case with overshoot the values for 20 TP are shown, of which about 10 are clustering at $\lambda \gtrsim 1$ because then, by definition, the core mass does not grow anymore. All models have solar metallicity

been shown by Herwig et al. (1997) that such a region follows naturally if depth dependent overshoot is considered which models an exponentially declining turbulent velocity field. During the following interpulse evolution ^{13}C forms. The ^{13}C burns under radiative conditions (Straniero et al., 1995) and releases neutrons via the reaction $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$. Current models of the s-process nucleosynthesis show that this is the dominant mechanism of heavy-element synthesis in low-mass AGB stars (Gallino et al., 1998). Together with the H-burning ashes the heavy elements formed by this mechanism are then engulfed by the He-flash convection zone and can reach the surface by the next dredge-up event.

Also note, that dredge-up below the He-flash convection leads to a phase where the temperature at the bottom of the convective boundary exceeds $T \simeq 2.7 \cdot 10^8\,\mathrm{K}$, which lasts for about $30\,\mathrm{yr}$ while models without overshoot have a much shorter high-T phase of only a few years.

2.2 The third dredge-up

Maybe one of the most compelling aspects of models with overshoot is the ease with which they produce low-mass carbon stars due to efficient dredge-up. For example, our M_{ZAMS}=1.7 $\mathrm{M}_{\odot}$, Z=0.02 model sequence becomes a carbon star after the 10$^{\mathrm{th}}$ TP when the hydrogen-free core has a mass of $M_{\mathrm{H}} \simeq 0.6\,\mathrm{M}_{\odot}$. The luminosities are $\log L \lesssim 4.1$, $\simeq 3.6$ and $\gtrsim 3.9$ at the TP luminosity maximum, minimum and during the quiescent interpulse phase. Similar results have also been found for models of lower metallicity and it seems that the problem of the theoretically missing low-luminosity carbon stars can be solved by some overshoot below the He-flash convection zone. The enhanced dredge-up efficiency is caused by the modification of the intershell abundance. The abundances found with overshoot show qualitatively the same dependence on the pulse number like models without overshoot (Schönberner, 1979; Boothroyd and Sackmann, 1988). However, with overshoot the intershell contains much more carbon and oxygen at the expense of helium. For example, for a $3\,\mathrm{M}_{\odot}$ stellar



(a) Without overshoot

(b) With overshoot

Figure 3: Abundance profile of AGB models in the region of the He- and H-burning shell.

model after the 13^{th} TP we find [He,C,O]=[0.39,0.41,0.16][1] whereas the values from calculations without overshoot are [He,C,O]=[0.70,0.26,0.01]. It has actually been found that the amount of overshoot applied to the bottom of the He-flash convection zone, the resulting helium abundance and the dredge-up after the TP are proportional (Herwig et al., 1999b).

The combined effect of efficient dredge-up and enhanced oxygen and carbon content in the intershell region inverts the common belief that AGB stars do not contribute to the Galactic oxygen production. Models with overshoot predict that a 3 $\mathrm{M}_\odot$ star of solar metallicity will eject about 0.03 $\mathrm{M}_\odot$ of primary ^{16}O which was formed by He-shell burning. Also, the surface abundance of oxygen (and thus the O/H ratio) is larger by about a factor of two to three due to overhoot. Unfortunately, the determination of the oxygen abundance in giant stars is difficult and yields sometimes ambiguous results (Fulbright and Kraft, 1999).

3 Evidence for overshoot in AGB stars from models and observations of post-AGB stars

In the previous section we have shown that overshoot from below the He-flash convection zone leads to important modifications of structure and chemical evolution of AGB stars. It is therefore important to collect evidence for the existence and efficiency of overshooting at this convective boundary. Such evidence comes from a class of H-deficient post-AGB stars with unusual surface abundances: the [WC]-type central stars of planetary nebulae (Koesterke and Hamann, 1997; Hamann, 1997; De Marco et al., 1998) and the PG 1159 stars (Dreizler and Heber, 1998; Werner et al., 1999). The spectroscopic abundance analysis revealed that these stars are very carbon rich and also *oxygen rich!*. Typically, one finds [He,C,O]=[0.50,0.33,0.17] for PG 1159 stars. In particular the large mass fraction of oxygen has been puzzling because AGB stellar models have shown such a high oxygen abundance only *below* the intershell and helium-burning region where the helium abundance is already much lower then the observed 50%. Thus, AGB models without overshoot do not show the observed abundance pattern of H-deficient post-AGB stars at any depth and, moreover, no scenario of combined mixing and mass loss could be identified to solve the problem. Almost any post-AGB evolutionary model sequence is H-normal (Blöcker, 1995). The only advance has been the discovery that a thermal pulse on the post-AGB, shortly before the star becomes a white dwarf, may lead to convective H-burning in the intershell during the He-flash (see Iben & McDonald (1995) and references there).

[1] All abundances are given in mass fractions.

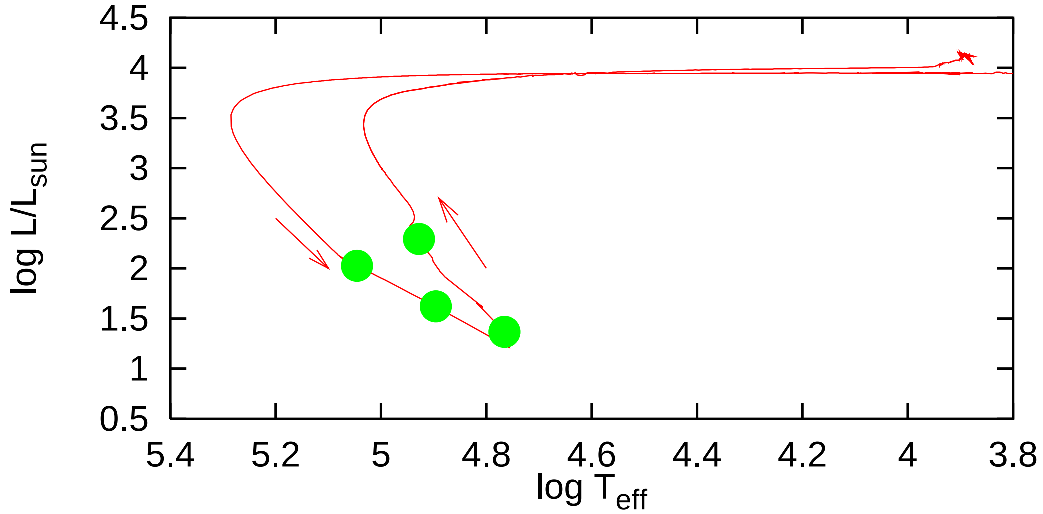


Figure 4: Post-AGB evolution with a very late thermal pulse and consecutive return into the AGB domain of the HRD. At the first mark along the track, the He-flash convection zone is already well established. At the second mark, the outwards growing convection zone has reached the envelope and protons start to enter into the convective zone were they are captured by ^{12}C *on the way*. At the third mark the hydrogen luminosity has reached its peak. The surface composition is hydrogen-free beyond the last mark.

This *very late* TP brings up the intershell abundance and thereby leads to a significant abundance change at the surface. However, the models which where available so far fail to predict the observed high abundance of oxygen.

With overshoot the abundances in the intershell coincide naturally with the abundance pattern found in the H-deficient post-AGB stars (Fig. 3). Also, a certain range of observed abundances may reflect the time and metallicity dependence of the intershell abundance. We have performed new stellar evolution calculations of the post-AGB phase which take the modifications of the intershell abundance of AGB stars due to overshoot into account. Also, we employ a time-dependent and coupled treatment of nuclear burning and convective mixing to correctly describe the nuclear processing of protons under the conditions encountered in the convectively unstable He-shell (for details see Herwig (2000)). We found that, within the very late thermal pulse scenario, H-deficient Born-again post-AGB stars (see Fig. 4) exhibit surface abundances (also for oxygen) and parameters in the range observed (Herwig et al., 1999a).

4 Conclusions

In this paper we have reported of interdependent advances of recent stellar evolution modeling of AGB and post-AGB stars which mutually add to their significance. Currently the modification of the intershell abundances following the overshoot concept appears to be the *only* possible theoretical explanation for the large oxygen abundances observed in H-deficient post-AGB stars. Thus, the application of some overshoot from below the He-flash convection zone of AGB stars solves a long standing observational puzzle.

In turn, this importance of AGB-overshoot for the H-deficient post-AGB stars presently is one of the strongest evidence that such overshoot is indeed operating. Also other problems can be resolved, like the modeling of carbon stars with low luminosities as observed in the Magellanic Clouds.

More support for the overshoot concept comes also from hydrodynamic modeling (see contribution by D. Arnett, this volume). On the other hand, we have so far not found any evidence against the operation of overshoot in AGB stars (though we might not have searched for it hard enough yet).

At the present stage we can conclude that the operation of some overshoot in AGB stars appears to be very likely. The consequences for the chemical yields and the enrichment are both qualitative and quantitative. While the larger dredge-up efficiency enhances the mass fraction of synthesized material in the ejecta in general also the relative abundance fractions are changed, which is most remarkably the case for oxygen.

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