TP-AGB EVOLUTION WITH OVERSHOOT FOR LOW-MASS STARS AS A FUNCTION OF METALLICITY

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ABSTRACT. We give a brief review on the properties of asymptotic giant branch models with overshoot. Then we describe new model calculations with overshoot. Initial masses are ranging from 1 to 3 $M_\odot$ and metallicities are Z=0.02, 0.01 and 0.001. Third dredge-up occurs efficiently for low masses and carbon stars are formed, with some at core masses as low as 0.58 $M_\odot$. After the thermal pulse at which stars become C-rich the luminosities are in the range of the observed C-star luminosity function during the whole interpulse phase and for all C-star models. The dredge-up evolution depends mainly on the core mass at the first thermal pulse and on the metallicity. The Z=0.001 models of the 2 and 3 $M_\odot$ sequence become C-rich almost instantaneously after the onset of the first thermal pulses. For the 2 $M_\odot$ case the C/O ratio initially exceeds 4. During following dredge-up episodes the C/O ratio decreases.

1. Introduction

In recent years we have studied the influence of overshoot on the evolution of asymptotic giant branch (AGB) stars by means of stellar modeling. Many aspects of the evolution of AGB stars have been found to be affected by overshoot and generally speaking the models with overshoot appear to be capable of solving a number of problems. This is in particular related to the ease at which they show the third dredge-up (DUP) and the modification to the internal abundance in the region between the nuclear burning shells (Herwig et al. 1997, Blöcker 1999, Mazzitelli et al. 1999).

A very important application and test of the AGB models with overshoot has been their use as a starting point for the investigation of evolutionary scenarios of H-deficient post-AGB models (Herwig et al. 1999a). Overshooting has been able to improve the models in two ways. First, it has been possible to identify dredge-up as a process to cause H-deficiency of post-AGB stars (Blöcker 2000, Herwig 2000). This opens new possibilities for the interpretation of the observational diversity of these objects. Second, all current evolutionary calculations of H-deficient post-AGB stars predict that the abundance ratio of (He/C/O) as observable at the surface is the same as the ratio in the intershell of the progenitor AGB star. As it appears to date only AGB models with overshoot are sufficiently abundant in oxygen in the intershell in order to reproduce the high observed oxygen mass fractions of post-AGB stars (e.g. Werner et al. 1998). These findings support the overshoot concept for AGB and post-AGB stars in general.

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While evidence for overshoot in AGB stars is growing many of the aspects studied have been accessed only in exemplary cases (like the $3\,\mathrm{M}_\odot$ one with $Z = 0.02$). However, comparison with observable properties of AGB stars as a population provide a key tool to constrain stellar modeling. For example, the comparison of a theoretical luminosity function (LF) of carbon stars with an observed one allows to constrain the efficiency of DUP. In order to utilize these constraints we compute a new model grid covering mass and metallicity. Previous efforts in this direction have returned valuable insights about the order of magnitude of DUP needed. For instance, Marigo et al. (1999) have found that the observed carbon star LF of the LMC can be reproduced by models with a DUP efficiency of $\lambda = 0.5$ starting at a minimum temperature at the bottom of the convective envelope of $\log T_\mathrm{b}^\mathrm{dred} = 6.4$ which corresponds in their analysis to a minimum core mass for DUP in the range $0.53 \ldots 0.58\,\mathrm{M}_\odot$. These studies further emphasize the need for mechanisms to enhance DUP in stellar models of thermal pulse AGB stars because the cited conditions cannot be met with standard models, e.g. those of Forestini & Charbonel (1997) or Wagenhuber & Groenewegen (1998). Clearly, overshoot is such a mechanism.

2. Properties of AGB stellar models with overshoot

During our previous studies we have identified five aspects of AGB stellar models which are modified by exponential diffusive overshoot which we always apply to all convective boundaries.

1. In the region between hydrogen and helium burning shells (intershell region) the helium abundance is decreased and carbon and oxygen is enhanced compared to the intershell abundances in models without overshoot. In particular the oxygen enhancement up to mass fractions of about 0.20 is typical for models with overshoot. This abundance change in the intershell is caused by a deeper penetration of the He-flash convection zone into the C/O core below. It may be referred to as "intershell DUP" or "fourth DUP".
2. This deeper penetration of the He-flash convection into the C/O core is closely related to the larger energy generation by He-burning during the thermal pulse (TP). Consequently, higher temperatures at the bottom of the He-flash convection zone and lower temperatures at the top are found, compared to models without overshoot.
3. These changes of structure and chemical composition in the intershell region substantially increase the efficiency of the third DUP of material from the intershell region into the envelope and up to the surface. The dredged-up material has a modified abundance distribution. More and different material is dredged-up than by models without overshoot. As a result models with overshoot have a different evolution of the surface abundances and show a stronger signature of nucleosynthesis. Due to efficient DUP the core mass during some more advanced TPs is constant or may even decrease.
4. The interpulse phase of an overshoot model sequence is characterized by a faster recovery of the hydrogen-burning shell after the TP. Consequently, the surface luminosity is recovering faster after the TP compared to models without overshoot.

5. At the end of the DUP a ^{13}C and a ^{14}N pocket at the envelope-core interface is formed which is presumably of importance for the nucleosynthesis in AGB stars.

3. Starting models and input physics

In our stellar evolution code (Blöcker 1995, Herwig et al. 1997) we now use the most recent *OPAL* opacities (Iglesias & Rogers, 1996) which have been complemented with low-temperature tables from Alexander & Ferguson (1994). The initial helium mass fraction has been chosen according to $Y = Y_{\odot} + \Delta Y/\Delta Z \cdot (Z - Z_{\odot})$, where $Y_{\odot} = 0.28$ is the value adopted for the solar initial helium abundance, $Z_{\odot} = 0.02$ is the solar metallicity. $\Delta Y/\Delta Z$ is the ratio of fresh helium supplied to the interstellar medium by stars relative to their supply of heavy elements. Here we have chosen a value of $\Delta Y/\Delta Z = 2.5$ (Pagel & Portinari 1998). The distribution of metals is according to Grevesse & Noels (1993) and Anders & Grevesse (1989), and scaled the isotopic abundance for non-solar metallicity. For the overshoot prescription see Blöcker et al. (this volume).

We have constructed pre-main sequence starting models from a polytropic structure and followed the entire evolution up to the AGB. During the main sequence evolution of models with a zero-age main sequence mass $M_{\mathrm{ZAMS}} \leq 1.5\,\mathrm{M}_{\odot}$ we have applied a reduced overshoot efficiency of $f = 0.008$ (Bressan et al. 1993, Ventura et al. 1998). Otherwise we used our standard value of $f = 0.016$. The evolutionary tracks in the HRD are in reasonable agreement with those computed by Schaller et al. (1992) with overshoot and low metallicity. The time step during the main-sequence evolution has been limited to 1/500 of the total main-sequence evolution.

Stars with $M_{\mathrm{ZAMS}} \leq 1.7\,\mathrm{M}_{\odot}$ suffer a central He-flash at the tip of the red giant branch (RGB). We did not calculate the central He-flash phase explicitely. Because chemical changes induced by the flash itself can be expected to be small, we construct zero-age horizontal branch models by calculating equilibrium models of given mass and chemical composition (i.e. mass and composition of the models at tip of RGB).

We have used a Reimers mass-loss rate (Reimers 1975) starting at the base of the RGB. For sequences with $M_{\mathrm{ZAMS}} \leq 1.7\,\mathrm{M}_{\odot}$ we choose $\eta_{\mathrm{R}} = 0.5$ and $\eta_{\mathrm{R}} = 1.0$ for larger M_{ZAMS}. Note, that the Reimers mass loss rate has not been designed for AGB models, and that this choice has mainly been made for compatibility with existing models of previous works. This approach is suitable to investigate the main trends.

In this context we should also mention a slightly different treatment of envelope overshoot during the actual DUP phase. Herwig et al. (1999b) and Mowlavi (1999) found that the DUP efficiency not much effected by variations of the overshoot at the bottom of the envelope convection. We found that the numerical resolution can be released if a larger overshoot parameter is applied during the actual DUP phase. While numerical and in particular time resolution needs to be very high with our original choice of the overshoot efficiency of $f = 0.016$ we have now used a ten times larger value during the period where the actual DUP takes place. During the interpulse period and at the bottom of the He-flash convection zone we use the original value of 0.016. Although a larger f-value can certainly not be excluded for physical reasons we consider it here just as a numerical method in order to save CPU time. Without this measure the computation of a grid in mass and metallicity would not be possible within reasonable time. With this increased value of f we can reduce the number of models needed to compute the DUP phase by a factor of ten. The trade-off for this treatment is that the DUP efficiency is larger by about 20% compared to our original treatment, and in some cases third DUP sets in one TP earlier than with the smaller f-value. This seems contrary to the above mentioned findings, but they do not refer to such large overshoot values.

4. The TP-AGB models

We have computed 10 TP-AGB model sequences with masses ranging from $1\,M_\odot$ to $3\,M_\odot$ and with metallicities Z=0.001, 0.01 and 0.02. The main interest in this study was the occurrence of the third DUP and the subsequent formation of carbon stars (Tab. I and II). Previous studies have revealed that DUP depends on core mass, metallicity, treatment of convection and envelope mass (Wood 1981, Lattanzio 1986).

The core mass at the first TP depends on the initial stellar mass, on overshoot and on metallicity. Models with main sequence core overshoot have larger core masses than AGB models without overshoot. For example the core at the first TP of our solar $3\,M_\odot$ sequence is about 10% more massive with core overshoot than without core overshoot. While the core masses of the Z=0.02 and 0.01 sequences are similar, the M2.0Z0.001 (meaning the sequence with a main-sequence mass of $2\,M_\odot$ and metallicity Z=0.001) and M3.0Z0.001 sequences have much larger core masses at the first TP. Due to the larger core mass the DUP is more efficient than for models with the same initial stellar mass but larger metallicity. The DUP of the Z=0.001 sequence is rather similar to those Z=0.02 sequences which have a similar core mass at the first TP. As can be seen in Fig. 1 the M2.0Z0.001 model sequence shows a similar DUP pattern as the solar $3\,M_\odot$ sequence, and the M1.7Z0.02 and the M1.5Z0.001 sequences are similar as well. Moreover we found that the solar $4\,M_\odot$ sequence of Blöcker et al. (this volume) shows a similar core mass evolution than our M3Z0.001 model sequence. Thus, we conclude that the DUP efficiency of TP-AGB models with overshoot is most importantly ruled by the core mass at the first TP.

Moreover DUP efficiency is directly enhanced by lower metallicity. This is evident from the two pairs of sequences shown in Fig. 1. For the Z=0.001 sequences the DUP (and the interpulse period) is somewhat larger than for the Z=0.02 sequence with the same core mass, although the latter has larger envelope masses. While the DUP difference among the Z=0.02 and Z=0.001 case is moderate, it is negligible among the Z=0.02 and 0.01 case.

Eventually recurrent DUP of carbon (and oxygen) from the intershell up to the surface leads to carbon star formation. All but the M1.0Z0.02 sequence, listed in Tab. I will become carbon rich. For the $1.5\,M_\odot$ sequences C-star formation is very likely but the computations have not been followed to the end. The M1.0Z0.02 sequence does not experience third DUP at all. After two TPs the AGB evolution is over because the envelope mass is lost by mass loss.

An important result are the low luminosities at the time when carbon stars are formed. The carbon star LF for the LMC peaks at $M_{\rm bol} = -4.9$ with tails reaching from $M_{\rm bol} = -3.2$ to -5.9 (Marigo et al. 1999, and references there). In Tab. II we

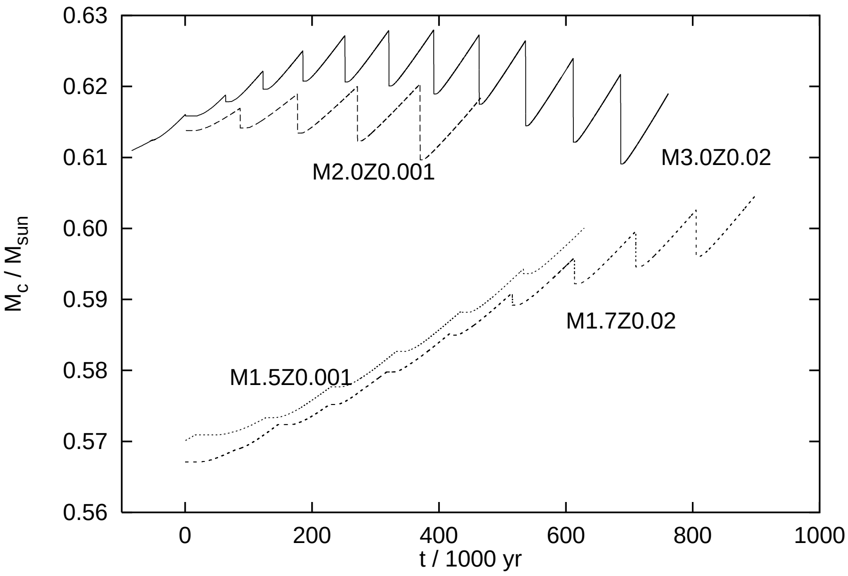

Fig. 1. Evolution of the hydrogen free core of four sequences with different mass and metallicity. The core mass grows due to H-shell burning and is reduced by DUP. Models with Z=0.001 show a similar DUP pattern as models with solar metallicity and a roughly 20% larger core mass.

give the largest and smallest magnitude during the interpulse phase which follows the TP of carbon star formation. All model magnitudes fall within the observed range. In particular, the M2.0Z0.01 sequence covers the low luminosity tail of the LF during the initial and shorter low luminosity phase of the interpulse period. During the longer high luminosity phase of the interpulse period the models have the luminosity of the LF peak. These new computations show that models with overshoot can produce carbon stars of sufficiently low luminosity.

The formation of carbon stars can proceed over many TPs with small increases of the C/O ratio at each TP. For example, the M2.0Z0.010 sequence needs 7 TPs from the start of DUP until the model is carbon rich. The other extreme are the more massive and very low metallicity model sequences which can become carbon rich at the first or second TP where DUP is instantly present. These models allow to study the variation of the surface C/O ratio as a function of pulse number which is of relevance for less massive and more metal rich models as well. This variation is displayed in Fig. 2 for the M2.0Z0.001 sequence. The C/O ratio in the intershell is very high during the first TP and decreases continuously over the following TP. This high intershell C/O ratio together with the lower absolute mass fractions of C and O in the envelope for Z=0.001 leads to an immediate transformation into a carbon star during the first DUP episode after the second TP. Following DUP episodes are even more efficient with $\lambda > 1$ and the C/O number ratio quickly reaches values as high as 4. However, at following TPs the C/O ratio is not increased by DUP but decreased. This is because the C/O ratio in the

TABLE I

Properties of TP-AGB model sequences with overshoot. The columns contain sequence identifier (ZAMS mass, metallicity), core and total mass at first TP, pulse number, core mass and total mass of first TP with DUP and for first TP with number ratio C/O $\geq$ 1.

sequence	M_c^1	M_*^1	$TP^{\rm min}$	$M_c^{\rm min}$	$M_*^{\rm min}$	$TP^{\rm C/O\geq 1}$	$M_c^{\rm C/O\geq 1}$	$M_*^{\rm C/O\geq 1}$
	[M$_\odot$]	[M$_\odot$]		[M$_\odot$]	[M$_\odot$]		[M$_\odot$]	[M$_\odot$]
M1.0Z0.020	0.526	0.561	No DUP, end of AGB after 2nd TP.					
M1.5Z0.020	0.559	1.240	(3)	(0.565)	(1.219)	See remark below.		
M1.5Z0.010	0.560	1.254	6	0.581	1.185	Last computed TP: 7, C/O=0.71.		
M1.5Z0.001	0.571	1.323	5	0.588	1.282	Last computed TP: 7, C/O=0.95.		
M1.7Z0.020	0.567	1.476	5	0.585	1.417	9	0.603	1.249
M2.0Z0.020$*$	0.477	1.889	16	0.573	1.638	22	0.601	1.479
M2.0Z0.010	0.508	1.920	7	0.534	1.844	14	0.578	1.600
M2.0Z0.001	0.614	1.868	2	0.617	1.858	TP(min)=TP(C/O $\geq$ 1)		
M3.0Z0.020	0.616	2.870	2	0.619	2.862	7	0.628	2.750
M3.0Z0.010	0.643	2.868	2	0.646	2.857	4	0.649	2.821
M3.0Z0.001		DUP after first TP leads to C/O=1.7.					0.813	0.278

M1.5Z0.020: Quenching (weak thermal runaway without He-flash convection zone) of second TP leads to stronger He-flash at third TP than usual. This causes third DUP after the third TP. No third DUP for TP 4 and 5. Then third DUP starting continuously at TP 6 with $M_c^{\rm min} = 0.584\,{\rm M}_\odot$. M3.0Z0.020: Before first TP one quenched TP. M2.0Z0.020$*$:Computed with an older code version and started with too small M_c^1. The new core mass at the first TP for this sequence is $0.505\,{\rm M}_\odot$.

TABLE II

Properties of TP-AGB model sequences with overshoot at that TP where C/O $\geq$ 1. The columns give sequence identifier, bolometric magnitudes after the TP at which C/O $\geq$ 1 ($M_{\rm bol,min}^{\rm C/O\geq 1}$ = magnitude immediately after the TP and $M_{\rm bol,ip}^{\rm C/O\geq 1}$ = magnitude towards the end of the interpulse period) DUP parameter λ, the age (first TP: $t = 0$yr) and the intershell abundance of helium, carbon and oxygen at this pulse.

sequence	$M_{\rm bol,min}^{\rm C/O\geq 1}$	$M_{\rm bol,ip}^{\rm C/O\geq 1}$	$\lambda^{\rm C/O\geq 1}$	$t^{\rm C/O\geq 1}$	$(He/C/O)_{\rm is}^{\rm C/O\geq 1}$
	[mag]	[mag]	[ratio]	[yr]	[mass fractions]
M1.7Z0.020	−4.31	−5.14	0.81	4.16E5	(0.32/0.45/0.20)
M2.0Z0.020$*$	−4.38	−5.16	0.65	4.09E6	(0.33/0.43/0.20)
M2.0Z0.010	−4.06	−4.84	0.54	2.30E6	(0.25/0.42/0.32)
M2.0Z0.001	−4.08	−4.77	0.87	8.64E4	(0.44/0.49/0.07)
M3.0Z0.020	−4.63	−5.28	1.13	3.92E5	(0.29/0.44/0.23)
M3.0Z0.010	−4.65	−5.25	1.36	1.75E5	(0.29/0.52/0.17)
M3.0Z0.001	−5.39	−5.62	1.90	0	(0.59/0.37/0.04)

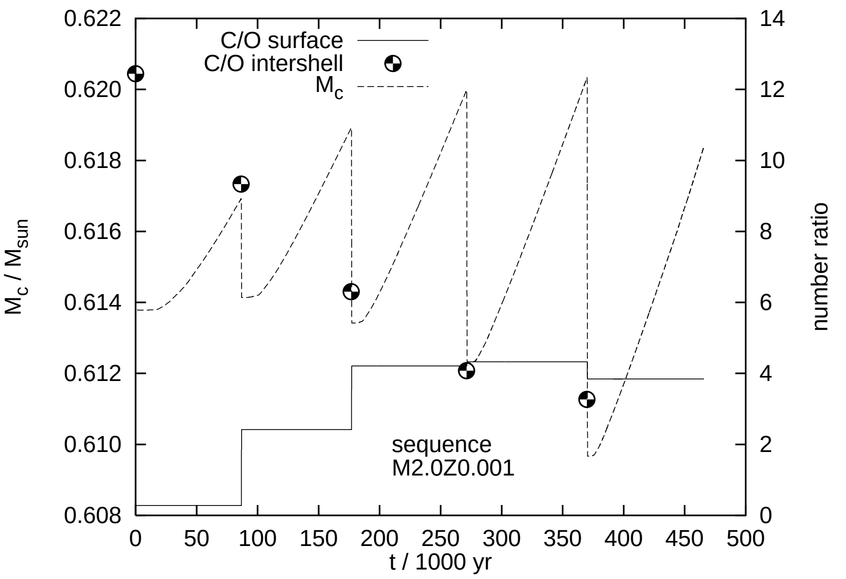

Fig. 2. Evolution of surface and intershell C/O ratio with time, $t = 0$yr at first TP. The C/O ratio at the surface initially increases sharply after the first TP with DUP because the C/O ratio is very high in the intershell and the absolute mass fractions of C and O are small in the envelope at low Z. After a few TPs the C/O ratio in the intershell has decreased drastically. This reduction then leads to a decrease of the surface C/O ratio as this intershell material is dredged-up.

intershell is decreasing at each TP during the first TP-AGB phase when more oxygen is mixed from the C/O core into the intershell region by intershell DUP. At the fourth TP of sequence M2.0Z0.001 (Fig. 2) the surface C/O ratio has reached the intershell C/O ratio. During the following TP the intershell C/O ratio will decrease further and then *DUP will decrease the surface C/O ratio.* For less massive or more metal rich stars the formation of C-stars is not fast enough in order to exhibit a surface C/O ratio maximum. However, it is clear that the surface C/O ratio in these stars will also asymptotically approach the intershell ratio, which is believed to show up at the surface of H-deficient post-AGB stars. Therefore, overshoot AGB models cannot produce too large C/O ratios, even if the mass loss is very small, as long as the intershell C/O ratio is small enough. Note, that the largest observed C/O ratio in stars or PNe (Zuckermann & Aller 1986) is of the same order as the typical asymptotic C/O intershell ratio.

5. Conclusion

We have studied the TP-AGB evolution of low mass stars as a function of metallicity. We find that C-star production at low core masses is possible with overshoot. Typically, carbon star models of low mass stars have core masses around $0.6\,M_\odot$. The C/O ratio asymptotically reaches the value of the intershell which is around 3 in models with overshoot. This may be a natural explanation why the largest observed C/O ratio in stars or PNe is actually at about this value. These models should help to evaluate the appropriateness of the overshoot concept for TP-AGB stars.

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