The fate of super-AGB stars at low metallicity

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Abstract. Super-AGBs are stars massive enough to ignite carbon off center and to climb the asymptotic giant branch (where they undergo thermal pulses) after core carbon exhaustion. The destiny of these stars, ONe white dwarfs or neutron stars, depends essentially on the ability of the mass loss to peel the stellar envelope before the core reaches the critical mass for electron captures to occur. Here, we focus on a super-AGB stars of 8.5 $M_\odot$ at Z=0.0001 and investigate the effects of various mass loss prescriptions. We study the interplay between mass loss and diffusive overshooting below the convective envelope. The former determines the duration of the AGB phase and the final state of the star; the latter affects the increase of the core mass and the nucleosynthesis as well.

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INTRODUCTION

Super-AGBs (sAGB) are stars in the mass range $\sim 8-11$ $M_\odot$ which bridge the gap between normal AGB stars and massive stars. They ignite carbon and form an ONe white dwarf before climbing the asymptotic giant branch. Compared to normal AGB stars, sAGB have not deserved much attention in the past years despite their many astrophysical interests. With their peculiar nucleosynthesis, they can be important contributors to the ISM enrichment. Miyaji & Nomoto (1987) and Nomoto (1987) first showed that a degenerate ONe core of 1.37 $M_\odot$ undergoes core collapse induced by electron captures. More recently, Ritossa et al. (1999) using fully consistent simulations reached the same conclusion. Ritossa et al. (1996) and Iben et al. (1997) also explored the thermally pulsing AGB phase of these stars.

It appears that the fate of sAGB strongly depends on the competition between mass loss rate and core growth rate during the AGB phase. On one hand indeed, core collapse occurs providing SN and a neutron star remnant if the mass of the white dwarf reaches 1.37 $M_\odot$. On other hand, if the mass loss is efficient enough to expel all the envelope before the core reaches this critical mass, the electron captures will be prevented. In this case the star forms a planetary nebulae and a ONe white dwarf.

Here we investigate the case of a star of 8.5 $M_\odot$ at low metallicity ($Z = 10^{-4}$) in order to address this last point. We use the stellar evolution code STAREVOL (see Siess et al. 1997, 2000 and Leclair et al. 2005 for more details). From the ZAMS up to the early-AGB phase we use the Reimers (1975) prescription for mass loss. The convective boundaries are identified with the Schwarzschild criterion, and no overshooting is included. Our nuclear network includes 53 species from protons to ^{37}Cl and fully accounts for the energetics of hydrogen, helium and carbon burning.

In the following we present the main features of the evolution of this star during the central combustion of H and He and the off-center C-burning. Then several assumptions are made to investigate the effects of mass loss and overshooting during the thermally pulsing sAGB phase.

FROM MS TO C-BURNING

Figure 1 presents the HR diagram for the 8.5 $M_\odot$ star at $Z = 10^{-4}$ and Tab. 1 resumes some typical quantities.

Because of its low metallicity this star does not climb the RGB after central H exhaustion and it does not undergo the first dredge-up, contrary to the model of Ritossa et al. (1996) at solar composition. Thus surface composition remains unaltered up to the occurrence of the second dredge-up on the early-AGB phase.

After central He-exhaustion, a degenerate CO core is built and the star ascents the AGB. The convective envelope sinks until it reaches the hydrogen burning shell. Surface abundances are modified by revealing CN-cycle products (the $^{12}C/^{13}C$ ratio falls from 90 to 17) and the Li abundance drops from $\varepsilon(\mathrm{Li}) = 2.6$ to 0.5.

Meanwhile as helium burns in shell, the CO core grows in mass. When it reaches 1.18 $M_\odot$, the maximum temperature reached is high enough to ignite carbon off-center. Due to the partial degeneracy of the plasma, a thermal runaway develops which generates a first con-

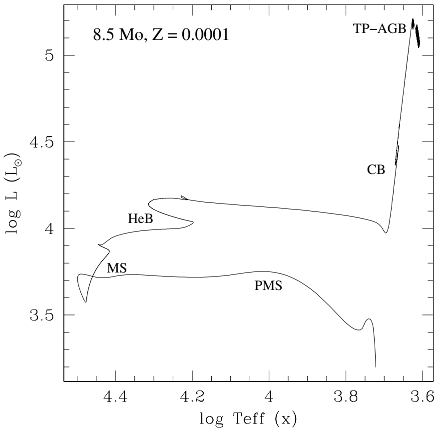

FIGURE 1. HR diagram of the 8.5 $M_\odot$, $Z = 10^{-4}$ star. Evolutionary phases are indicated: pre main sequence (PMS), main sequence (MS), central Helium burning (HeB), carbon burning (CB) and thermal pulses (TP-AGB).

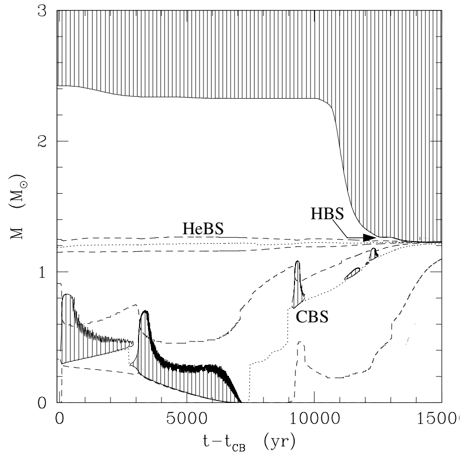

FIGURE 2. Kippenhahn diagram during the carbon burning phase: hatched areas correspond to convective regions, dotted and dashed lines indicate the maximum, the upper and lower limits of the burning zones for carbon, helium and hydrogen. Time is counted from the onset of the first carbon flash.

vective zone (see Fig. 2) The nuclear energy released during the C flash ($L_C = 1.4 \times 10^6$ $L_\odot$) produces an expansion of the shells surrounding the core which in turn alleviates the weight of the central layers. As a result, the core expands as the envelope is pushed outward. The inner temperature and density decrease and carbon burning is quenched. So the convective zone retracts when the carbon luminosity drops.

With the decline of nuclear energy production, core contraction resumes until the temperature reaches $\sim 6 \times 10^8$K and carbon ignites again in a new convective zone, deeper in the star. However during this second carbon ignition, the matter has a lower degeneracy so the flash is less violent and the shells beneath the convective carbon burning zone are less expanded than in the first case. An energy balance between neutrino loss and nuclear energy production can be achieved and a steady carbon burning flame is now propagating toward the center.

Carbon burning mainly produces ^{20}Ne and releases a substantial number of α particles which react mostly with ^{16}O. When the carbon flame reaches the center, after ~ 4000 yr, the core is mainly made of ^{16}O and ^{20}Ne with mass fractions of 0.65 and 0.26, respectively. ^{23}Na and ^{24}Mg contribute to a level of 4 and 2 %. Other species like ^{21}Ne, ^{12}C and ^{27}Al act as traces elements.

TABLE 1. Lifetime of main sequence and He burning phase, and core mass for the 8.5 $M_\odot$, $Z = 0.0001$ star. For carbon burning and second dredge-up, time is counted from the onset of the first carbon flash.

Phase	lifetime yr	M_{He} $M_\odot$	M_{CO} $M_\odot$	M_{ONe} $M_\odot$
MS(end)	25.7 (6)	1.18	–	–
HeB(end)	4.6 (6)	2.28	1.07	–
CB(begin)	0	2.30	1.18	–
CB(center)	7.1 (3)	2.30	1.21	0.64
2DUP	1.3 (4)	1.228	1.227	1.21

Then carbon burning occurs in shell around the ONe core. In our calculation three secondary convective pockets form outside the core due to the release of energy by the burning of some remaining carbon (Fig. 2).

At the end of the central carbon burning phase, the convective envelope sinks again and the second dredge-up is completed as it reaches the bottom of the helium burning shell. Helium is brought to the surface and its abundance raises from 0.25 to 0.36. Metallicity increases by a factor of 6 mainly due to primary ^{12}C, built in the He burning shell. Some primary ^{16}O and ^{14}N are also brought to the surface.

After the completion of the 2DUP, hydrogen burning resumes in a shell while carbon burning is ending. Thermal pulses then develop around a ONe core of 1.22 $M_\odot$. At the beginning of this phase, only 10^{-3} $M_\odot$ has been lost by the stellar wind.

AGB PHASE

Assumptions to calculate the TPAGB phase

In order to investigate in more detail the fate of sAGB stars, we started tests computations at the beginning of the early-AGB following the formation of the ONe core, using different assumptions on mass loss and mixing:

- Case $\mathscr{A}$ is computed with a high mass loss rate

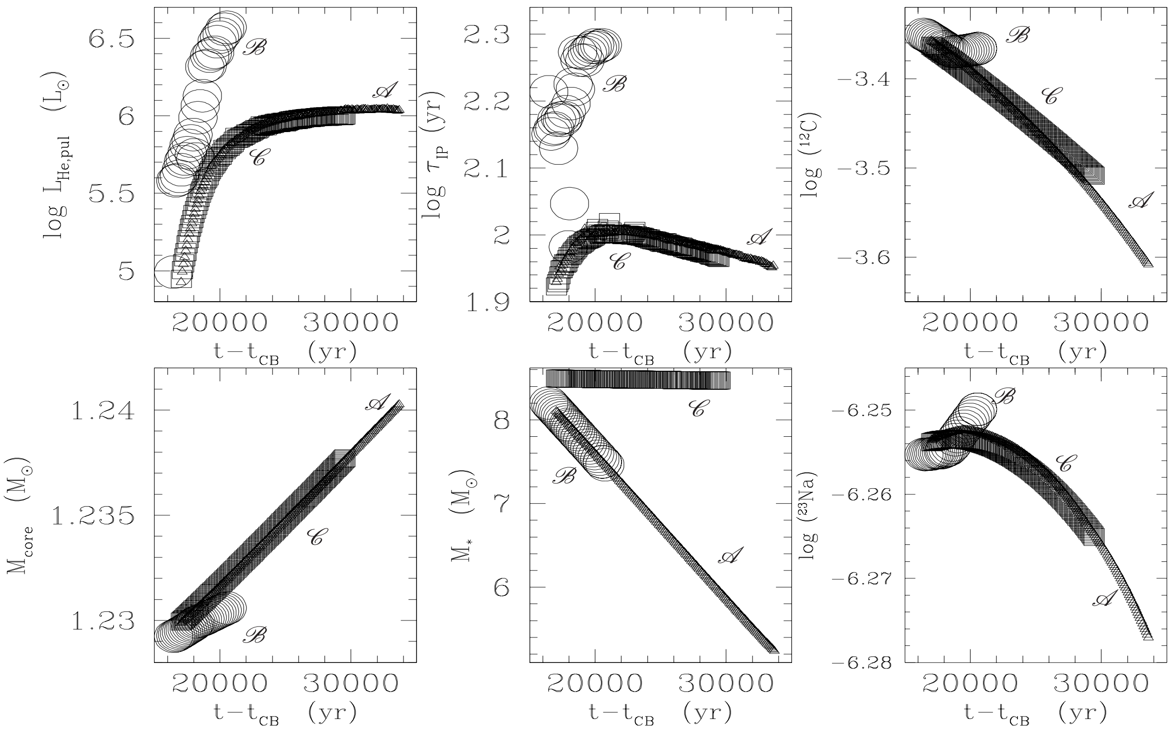

FIGURE 3. Maximum helium luminosity during a pulse (top, left), duration of the interpulse (top, center), mass of the core (bottom, left), mass of the star (bottom, center), surface mass fraction of ^{12}C (top, right) and of ^{23}Na (bottom, right) at each pulse during the TPAGB phase for case $\mathscr{A}$ (small triangles), $\mathscr{B}$ (circles) and $\mathscr{C}$ (squares). Time is counted from the onset of the first carbon flash.

given by Blöcker (1995) usually recommended for AGB stars, and without mixing except convection.

- Case $\mathscr{B}$ uses also Blöcker (1995) mass loss rate, but diffusive overshooting following Herwig (2000) below the envelope is added in order to trigger third dredge-ups (3DUP) and to explore the consequences of these events for the evolution of the star.
- Case $\mathscr{C}$ is computed with a lower mass loss rate as prescribed by the Jager et al. (1998) formulation, and without overshooting.

In all cases, the mass loss rate is scaled by a factor $\sqrt{Z/Z_\odot}$.

Fig. 3 shows some characteristics for these three cases: maximum He luminosity during the pulse (L_{He}), duration of the interpulse (τ_{IP}), core, stellar mass and surface abundances of ^{12}C and ^{23}Na are also given at each pulse.

Standard case

Case $\mathscr{A}$ has been evolved through 176 pulses which represents 18000 yr of evolution. Compared to standard AGB models of lower mass, the thermal pulses are weaker as helium luminosity saturates around 10^6 $L_\odot$. With a mean duration of about 1 year, the thermal pulses are short. They are also frequent since the interpulses last only ~ 100 years.

As we use the strict Schwarzschild criterion to define the convective limits, this model does not suffer 3DUP episodes. Only the very efficient hot bottom burning ($T_{BCE} = 130 \times 10^6$ K) at the base of the convective envelope is able to modify the surface abundances during the AGB phase. Carbon and oxygen are efficiently converted into nitrogen due to CNO cycles. NeNa and MgAl chains are also activated. Fig. 3 shows effect of CN cycle on ^{12}C and the destruction at high temperature of ^{23}Na to the benefit of ^{24}Mg mainly.

In case $\mathscr{A}$, the mass loss rate reaches 1.6×10^{-4} $M_\odot$ yr^{-1} at the end of the computation and by this time the star has lost 3.3 $M_\odot$. Meanwhile the He-free core grows from 1.228 $M_\odot$ to 1.240 $M_\odot$. A crude extrapolation of these data indicates that the envelope will be completely expelled well before the core reach 1.37 $M_\odot$ and hence the core will avoid electron captures core collapse. This star will most certainly form a planetary nebulae and a ONe white dwarf with a core mass of 1.228 $M_\odot$ surrounded by a CO layer of 0.03 $M_\odot$.

Effect of overshooting

Case $\mathscr{B}$ allows us to investigate the effect of overshooting on the evolution during the AGB phase. This model has been evolved through 28 thermal pulses. Overshooting induces mixing at the bottom of the convective envelope and allows substantial 3DUP to develop with $\lambda \sim 0.5$. After the passage of the convective envelope in the pulse region, it takes much longer for the He-burning shell to re-activate. So, compared to case $\mathscr{A}$, the interpulses last longer (twice as long) and the thermal pulses are stronger . These effects are mainly a consequence of a larger core mass at the time of He-runaway.

The 3DUP also changes the surface abundances as the convective envelope penetrates the pulse region where elements like ^{12}C, ^{16}O and ^{22}Ne are synthesized. When these elements are mixed in the convective envelope, because of efficient HBB, they suffer proton captures and, e.g. ^{22}Ne is converted into ^{23}Na.

Overshooting modifies the growth of the core because it triggers and amplifies 3DUPs. But the growth of the He-rich buffer is also altered during the interpulse as protons are mixed below the envelope. This mixing contributes to the continuous replenishment of the H-burning shell and incidentally it modifies its growth rate which in this case is reduced.

Compared with case $\mathscr{A}$, this model loses the same amount of mass by stellar wind but its core grows slower. Therefore these two models will share the same fate: formation of ONe white dwarf will a small external CO layer.

Effect of mass loss

The effect of mass loss is investigated in case $\mathscr{C}$ which has been calculated with the lower mass loss rate of de Jager et al. (1988). Fig. 3 reveals that the pulse characteristics are similar to case $\mathscr{A}$. They have comparable interpulse duration, strength in terms of He luminosity and the core grows at the same pace. With a similar temperature at the bottom of convective envelope, the evolution of the surface abundances for cases $\mathscr{A}$ and $\mathscr{C}$ show the same trends.

However, for this model the mass loss rate hardly reaches 1.9×10^{-6} $M_\odot$ yr^{-1} compared to 1.6×10^{-4} $M_\odot$ yr^{-1} in case $\mathscr{A}$, so at this point this models has lost only 0.03 $M_\odot$ during the first 136 pulses. During that period, the core has grown from 1.228 to 1.237 $M_\odot$ and based on these values, it will take 3×10^5 yr to reach the critical mass of 1.37 $M_\odot$ where electron captures start. With this assumed mass loss rate, 0.5 $M_\odot$ will be lost in the same time, so this star will most certainly end up forming a neutron star.

Adding overshooting to this model would lead to a slower increase of the core size (see case $\mathscr{B}$), extending the sAGB phase and thus increasing the amount of mass potentially lost. However, with a dredge-up parameter $\lambda = 0.5$, overshooting will not prevent the SN explosion.

CONCLUSIONS

We have computed a 8.5 $M_\odot$ star at $Z = 10^{-4}$ from PMS to the thermally pulsing sAGB phase. This star ignites carbon off-center and after the formation of a ONe core, pulses develop. We then investigate the effects of mass loss and envelope overshooting. Our main results are:

- models with a high mass loss rate will form a planetary nebulae and a ONe white dwarf.
- models with low mass loss rate will allow the core to grow up to the critical mass of 1.37 $M_\odot$ where electron capture will induce core collapse and the formation of a neutron star.
- as far as the dredge-up parameter remains moderate, overshooting seems to have only a secondary role in controlling the outcome of this evolution. But values of λ larger than 1, as found by Herwig (2004) in low metallicity stars, would change the picture. On the other hand, overshooting triggers the 3DUP events and therefore it modifies surface abundances and incidentally the stellar yields.

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