Thermally Pulsing AGB Models of Intermediate Mass Stars

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ABSTRACT. We present a set of models of AGB stars with initial mass larger than 5 $M_\odot$, as obtained with the FRANEC code. It includes model of Z=0.02 and Z=0.001, with and without mass loss.

1. Introduction

In the last years we have computed several sequences of AGB models of intermediate mass stars with the purpose to investigate the evolutionary properties and the related nucleosynthesis of these class of objects. In this paper we have collected all these models in order to summarize our main findings. In Table 1 we report a list of the computed sequences. Some features of the models are reported too. Let us remind that the models presented here have been obtained with the same version of the FRANEC code used in our previous computation of low mass AGB stars (Straniero et al. 1997).

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Mass & 5 & 6 & 7 & 5 & 5 \\
\hline
Z & 0.02 & 0.02 & 0.02 & 0.02 & 0.001 \\
\hline
Y & 0.28 & 0.28 & 0.28 & 0.28 & 0.23 \\
\hline
Mass loss & no & no & 3 & 10 & no \\
\hline
N. of TPs & 58 & 51 & 59 & 23 & 40 \\
\hline
Final Mass & 5 & 6 & 6.42 & 2.48 & 5 \\
\hline
Final C/O & 0.9 & 0.52 & 0.34 & 0.6 & 1.94 \\
\hline
$T_{BCE}$ & 46 & 69 & 82 & 17 & 73 \\
\hline
$T_{CSH}$ & 361 & 356 & 360 & 345 & 370 \\
\hline
$\Delta M_{DU}$ & 1.3E-3 & 6.5E-4 & 2.2E-4 & 1.4E-3 & 1.2E-3 \\
\hline
\end{tabular}
\caption{Tab. 1}
\end{table}

The ten rows in Table 1 report respectively: the initial mass (ZAMS mass) of each sequence, the initial metallicity, the initial helium, the adopted mass loss rate (“no”
Fig. 1. Evolution of the inner edge of the convective envelope together with the location of the H burning shell and the location of the He burning shell, for the 5 $M_\odot$ Z=0.001.

means no mass loss, while numbers indicates the value of the $\eta$ parameter in the Reimers formula), the numbers of computed thermal pulses, the final (last computed) mass, the final (last computed) carbon over oxygen ratio, the maximum temperature (in 10$^6$ K) at the base of the convective envelope (generally it coincides with the one obtained in the last computed interpulse except in the case of the 5 $M_\odot$ $\eta = 10$), the maximum temperature (in 10$^6$ K) at the base of the He convective shell and, finally, the last computed value of the amount of mass (in $M_\odot$) dredged from the He-core. Note that all the sequences (except the one of the 5 $M_\odot$ with $\eta = 10$) were arbitrarily stopped after about 40-50 TPs. The case of the 5 $M_\odot$ with $\eta = 10$ will be discussed below.

2. The III dredge-up

At variance with low mass stars, the III dredge-up (TDU) occurs rather early in our thermally pulsing intermediate mass models. For Z=0.02, the first evident episode is found after the 4th, the 5th and the 7th thermal pulse in the 5, 6 and 7 $M_\odot$ respectively, whereas at Z=0.001 the 5 $M_\odot$ experiences a TDU just after 3 TPs. The positions of the H and He burning shells as well as the position of the base of the convective envelope are reported in Figure 1, for the 5 $M_\odot$ Z=0.001. We found that the penetration of the convective envelope into the He core decreases when the mass increases (see the last row in Table 1). In addition the extension (in mass) of the region between the two burning shells is lower for the more massive models. These occurrences are probably due to the connection between the strength of the pulse and the efficiency of the Hydrogen burning shell (HBS). In fact the ignition point of the He burning shell (HeBS) in the temperature/density plane depends on the H burning rate. The larger this rate the lower the density and the larger the temperature of the He shell at the moment of the re-ignition. Then, less work must be done by the He burning to expand the lighter layers.
above it and, in turn, a weaker pulse and a smaller TDU occur. In the last computed pulse of the $5\,M_\odot$ the $3\alpha$ luminosity peak exceeds $10^8\,L_\odot$, but it drops to $6\cdot10^7$ and $2\cdot10^7\,L_\odot$ in the 6 and 7 $M_\odot$ models, respectively (see also Figure 2 and 3).

The more massive models have a more efficient HBS because of the larger core mass and the deeper penetration of the H rich convective envelope into the burning region (see next section). We have tested such a connection between H burning efficiency, pulse strength and TDU, by artificially reducing (or increasing) the rate of the $^{14}\text{N}(p,\gamma)^{15}\text{O}$, which is the bottleneck of the CNO cycle. This test confirms our hypothesis and allow us to conclude that any input physics, which could alter the rate of the H burning, have a direct influence on the features of the thermal pulse, in particular its strength and
3. Hot Bottom Burning

The evolution of the temperature at the bottom of the convective envelope (TBCE) for our 7 $M_\odot$ model of solar chemical composition is reported in Figure 4. We can see that this temperature rapidly approaches $8 \cdot 10^7$ K. Similar values were obtained by Blöcker (1995) for a 7 $M_\odot$ and by Lattanzio et al. (1996) for a 6 $M_\odot$. As shown in Figure 5 these temperatures are so large that most of the carbon dredged up from the He shell by the TDU is converted into nitrogen during the interpulse. A similar situation is found for
the 6 $M_{\odot}$, although the maximum TBCE is slightly lower (about $7 \cdot 10^8$ K). However, the $^{12}\text{C}(p,\gamma)^{13}\text{N}$ reaction is almost inactive at the base of the convective envelope in the 5 $M_{\odot}$. In this case the maximum TBCE never exceeds $5 \cdot 10^7$ K.

As already noted by Lattanzio et al. (1996) HBB is strongly limited by mass loss. In the extreme case of the 5 $M_{\odot}$ $\eta = 10$ the maximum TBCE does never reach $2 \cdot 10^7$ K.

At lower metallicity, the thickness of the HBS is larger and the penetration of the convective envelope into the region of the CNO burning is favored by a less steep entropy barrier. In our 5 $M_{\odot}$ $Z=0.001$, we found a bottom temperature as large as $7 \cdot 10^7$ K and a significant HBB. (see Figure 6 and 7). This is in agreement with the result of Lattanzio & Forestini (1999).

As firstly found by Blöcker & Schönberner (1991) in numerical computations of AGB stars, the classical core mass/luminosity relation (Paczynski, 1975, Iben & Renzini 1983) cannot apply to stars which experience HBB. Although we found a certain deviation from the classical relation, the luminosity of our more massive models, which are close to $M_{\text{up}}$ (i.e. the minimum mass for the degenerate carbon ignition), never exceeds the observed magnitude of the AGB tip ($M_{\text{bol}} \sim -7$, see e.g. Wood et al. 1992). In Figure 8 we report the luminosity versus the core mass for our model of 7 $M_{\odot}$. Note how the luminosity of these models asymptotically approaches the observed AGB limit.

4. Neutron source and s-process nucleosynthesis

At the time of the TDU, if a certain amount of protons are diffused below the convective envelope into the top layer of the Helium/carbon rich region, a tiny $^{13}\text{C}$ pocket forms. Later on, as already found for low mass stars (Straniero et al. 1995, Straniero et al. 1997, Herwig et al. 1997), when the temperature in that pocket rises up to 90-100 $10^6$ K, the $^{13}\text{C}$ is fully destroyed by $\alpha$ capture during the interpulse. So neutrons are released and the heavy s-elements production can take place. In such a case the typical neutron
density is of the order of $10^7 - 10^8$ n/cm$^3$. In our models with $M \geq 5 M_\odot$, a further neutron source operates during the convective thermal pulse. In fact, as shown in Table 1, the temperature at the base of the He convective shell reaches $3.5 \cdot 10^8$ K. In such condition, the substantial activation of the $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ reaction provides an important contribution to the $s$-process nucleosynthesis. This confirms the old prescription of Iben (1975a,b). The neutron density during the TP is definitely greater than in the case of the $^{13}\text{C}$ burning. We found $\rho_n \sim 10^{11}$ n/cm$^3$. Some details of the nucleosynthesis in intermediate mass stars can be found in Vaglio et al. (1999).

5. Termination of the AGB

The search of the physical mechanism responsible for the formation of a Planetary Nebula is a longstanding problem in modern astrophysics. This subject is obviously related to the comprehension of the final stage of the AGB evolution. In model computations it is currently assumed that, at a certain point along the AGB, mass loss abruptly grows (up to $10^{-5} - 10^{-4} M_\odot/yr$), so that an envelope ejection is simulated (see e.g. Vassiliadis & Wood, 1993; Blöcker, 1995; Forestini & Charbonnel, 1997). However, the correct evaluation of the masses of planetary nebulae and those of their nuclei, as well as the description of the AGB termination will depend on the particular parameterization of this superwind regime.

In a recent paper Sweigart (1998) found that in mass losing models the ratio ($\beta$) of the radiation pressure to the gas pressure drops abruptly in a region located just above the H/He discontinuity. This occurs just after each thermal pulse. When the envelope mass is reduced enough (how much is depending on the core mass and metallicity), $\beta$ becomes practically 0 and the local stellar luminosity exceeds the Eddington luminosity. Then, an instability, which could drive the envelope ejection, settles on. Something similar was also reported by Wood & Faulkner (1986).
Fig. 8. The core mass/luminosity relation for the $7 \, M_\odot$. Solid line represent the maximum luminosity during the interpulse. The two dashed line indicate the classical relation by Paczynski (1975, P75) and that by Iben & Renzini (1983, IR83). The observed AGB limit (Wood et al., 1992) is reported too.

Fig. 9. The ratio of the gas pressure to the radiation pressure in the last computed model of the $5 \, M_\odot \eta = 10$. The upper part of the He core and the most internal region of the convective envelope are shown.
We confirm the Sweigart’s finding. In our $5 \, M_\odot \, \eta = 10$ the minimum value of $\beta$ is attained during the TDU. At the beginning of the TP-AGB phase, the value of this minimum is about 0.3-0.4, but it decreases from one pulse to the next as the envelope mass is reduced by the mass loss. After 23 thermal pulses, when the residual total mass is $2.48 \, M_\odot$ and the core mass is $0.89 \, M_\odot$, $\beta$ goes to 0 and our hydrostatic code cannot go ahead (see Figure 9). We found the same situation in a $2.5 \, M_\odot$, $Z=0.006$ and $\eta = 2$. In such a case the final (last computed) mass is $0.81 \, M_\odot$ and the core mass is $0.67 \, M_\odot$.

Such an occurrence have a quite simple explanation. As a consequence of the thermal pulse, an expansion, starting from the He shell, propagates toward the surface. When this expansion reaches the base of H rich envelope, the local temperature decreases below $10^6$ K. Then the drop of $\beta$ is determined by the well known bump in the metal opacity around $\log T=5.3$ (see e.g. Iglesias, Roger, Wilson, 1992), which implies a decrease of the local Eddington luminosity. Thus a sort of void forms between the core and the envelope (see Figure 9). In this thin layer the stellar structure cannot react, as usually occurs, to an increase of the local temperature by expanding the gas and reducing the local pressure. Then, any small perturbation will inevitably grow. We cannot say if this instability can indefinitely grow, but we believe that this phenomenon could play a pivotal role in the AGB termination. This problem deserves a further investigation, possibly by means of an hydrodynamic code. Let us finally note that the TDU increases the metal content of the envelope, and, in turn, the opacity bump will increase. So the larger the dredge-up the deeper the $\beta$ drop is. In the present computations the final C/O ratio in the envelope of the $5 \, M_\odot$ is 0.6, whereas in the case of the $2.5 \, M_\odot$ we obtain a carbon star well before the end of the sequence.

Acknowledgements

This work was partially supported by the MURST Italian grant Cofin98, by the MEC Spanish grant PB96-1428, by the Andalusian grant FQM-108 and it is part of the ITALY-SPAIN integrated action (MURST-MEC agreement) HI1998-0095.

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