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On the nature of the thermal pulses on the asymptotic giant branch

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Abstract. We show that the amount of energy produced by a thermal pulse corresponds to the transition between two different eigenstates, one accretion-controlled and the other burning-controlled. It is the coupling between the large amount of energy required to perform such a switch and the fast injection of this energy in the star (a consequence of a thermal instability caused by the steepness of the 3α rate) that determines the recurrence of the thermal pulses and hence the existence of this evolutionary phase.

Key words. stars: evolution – stars: interiors – stars: AGB and post-AGB – stars: thermal pulses

1. Introduction

Schwarzschild & Härm (1965) were the first to recognize that the double shell burning phase occurring on the asymptotic giant branch (AGB) was not a steady state burning but that the two shells activate alternatively and that the He activation occurs through an instability (on a very short timescale) called a thermal pulse (TP). They studied in detail what causes such an instability and presented both a physical explanation and an analytic analysis of it. However they did not address at all (almost) the question of the amount of energy produced by this instability. After that pioneering paper, only few papers by Unno (1970), Dennis (1971), Sackmann (1977), Yoon et al. (2004) and Lattanzio & Wood (2004) have been devoted to the understanding of the growth of these instabilities and, as far as we know, only one Sackmann (1977) addressed the problem of the quenching of the thermal pulses: none of them discussed the amount of energy produced in a TP. This is an interesting, important point because the *recurrence* of the TPs (that is the basis of the existence of a TP-AGB evolutionary phase) depends on the fact that the energy produced by a TP is large enough to freeze the H-burning shell and therefore the growth of the He core: in fact only in this case the quiescent He burning phase that is set up after the damping of the thermal instability, is forced to come to an end as it approaches the border of the He core and a new duty cycle can start. If the energy produced by a TP were not powerful

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enough to freeze (or at least to slow down) the growth of the He core, the star would simply settle to a steady double shell burning.

In the next section we will show that it is possible to understand (both qualitatively and quantitatively) why each TP produces so much energy. We first discuss some general properties of the He-burning shell and then the growth and damping of a TP in more detail. Given the importance of the AGB, such an enormous amount of literature exists on this subject that is impossible to properly cite here. Hence we think it fair just to refer the reader to two review papers by Iben & Renzini (1983) and Herwig (2005) on the subject and to the excellent book specifically devoted to the AGB, evolution, nucleosynthesis and pulsation by Habing & Olofsson (2003).

2. The shell He burning and the onset of instabilities

Central He exhaustion forces He burning to shift in a shell that begins to advance in mass. The typical $\log(T) - \log(\rho)$, T-RO, relation attained within such a shell is shown in Fig. 1 for three cases that span most of the range of masses that form an advancing He-burning shell. Each curve represents the T-RO relation at a given time within the region included between $10^{-3} < Y < 0.9$ while each sequence (solid, dotted and dashed) represents the temporal evolution of the He shell for a specific mass. The three stellar evolutionary sequences presented in Fig. 1 have been computed with the Grevesse et al. (2007) solar chemical composition: $Z = 1.23 \times 10^{-2}$ and $Y = 0.257$ and $\alpha = 1.8$. The initial He abundance Y and mixing length parameter α have been derived, as usual, by fitting the current properties of the Sun. Figure 1 shows quite clearly that all the curves share a quite similar shape but quantitative zero point differences. This means that the T-RO relation in a steady burning shell complies with a quite universal shape while the zero point is mainly a function of the CO core mass size. By the way, this is the kind of relation that allows the He shell to advance in mass through a quiescent burning.

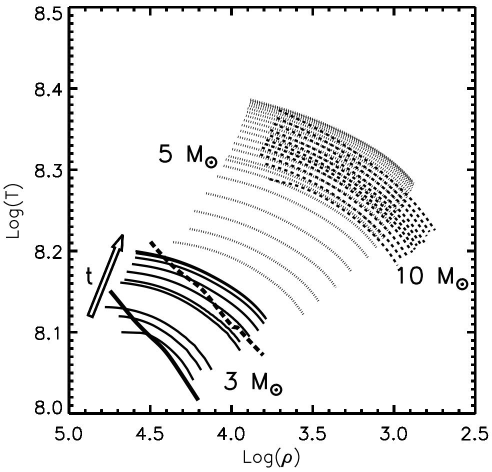

Fig. 1. $\log_{10}(T/K)$ to $\log_{10}(\rho/\mathrm{g\,cm^{-3}})$ relation within the He-burning shell ($10^{-3} < Y < 0.9$) in the early AGB for three stellar masses. The solid lines refer to the $3\,M_{\odot}$ star at different times, while the dotted and dashed lines refer to $5\,M_{\odot}$ and $10\,M_{\odot}$ stars. The initial chemical composition is $Z = 1.23 \times 10^{-2}$ and $Y = 0.257$ and the mixing length parameter $\alpha = 1.8$. The thick solid and dashed lines refer to $3\,M_{\odot}$ and $6\,M_{\odot}$ stars just before the start of a TP.

Once the He-burning shell quenches because of the thermostatic effect of the H-rich mantle, the H-burning shell re-activates, beginning to deposit fresh He on top of the now almost inert He core. This means that the T-RO relation within the He zone is now modelled and controlled, by the accretion rate and not by the presence of an active He-burning shell. As an example, the two thick lines in Fig. 1 show a typical T-RO relation in the interpulse region just before the start of a TP for stars of $3\,M_{\odot}$ (thick solid line) and $6\,M_{\odot}$ (thick dashed line). It is evident that (as we might expect) such a profile does not have anything to do with a burning profile. On the other hand the continuous growth of the He core, and hence of the temperature, necessarily leads to the He ignition (where the 3α rate reaches its maximum). The critical issue is that at this point the star tends to turn towards a steady He burning state (similar to that typical of quiescent

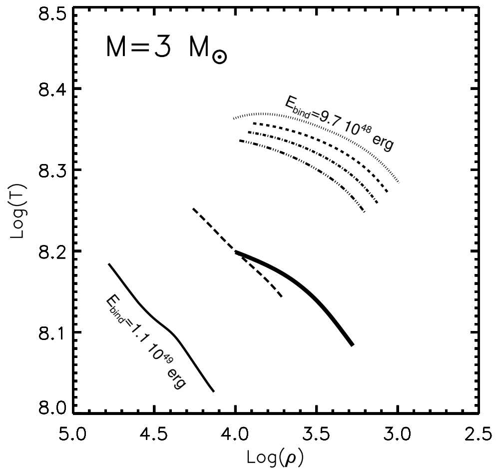

Fig. 2. $\log_{10}(T/\mathrm{K})$ to $\log_{10}(\rho/\mathrm{g\,cm^{-3}})$ relation within the He-burning shell ($10^{-3} < Y < 0.9$) at different phases along a TP duty cycle The solid line is the pre-pulse intershell region, the dotted line is the beginning of the steady He burning phase and the short-dashed, dot-short dashed and double-dot-short dashed lines refer to different times during the lifetime of the He-burning shell. The thick solid line shows the steady state condition that is obtained with the fake 3α cross section (see text).

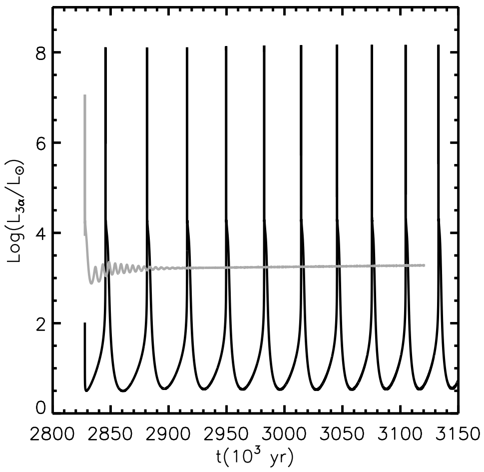

Fig. 3. Comparison between the 3α luminosity produced by the standard evolution of a 3 $M_\odot$ star (black line) and a test evolution (grey line) in which the cross section of the 3α process has been substituted with that of the ^{14}N(p,γ) scaled down by a factor of about 2.5×10^{12}.

He burning, shown in Fig. 1) but the switch from the accretion-controlled to the burning-controlled intershell structure implies a large change in the binding energy. For example, in the 3 $M_\odot$ case, the typical gravitational binding energy of the intershell at the moment of the He ignition (arbitrarily chosen when $L_{\mathrm{He}} = 10^{-2}\,L_{\mathrm{surf}}$, the precise time being unimportant) is of the order of 1.1×10^{49} erg while it becomes of the order of 9.7×10^{48} erg once the steady He-burning phase starts (arbitrarily chosen when L_{He} drops below 1.5 L_{surf}, the precise time being unimportant again). The energy liberated during the 3α luminosity peak is simply the one necessary to allow such a change of the binding energy and, in fact, in the 3 $M_\odot$ case the energy produced by the 3α luminosity peak amounts to 1.3×10^{48} erg. I.e. the value required to switch between the two physical states. Note that the surface losses in this time interval are negligible because they amount to roughly 10^{47} erg. Once the shift towards the steady burning configuration has come to completion, the steady He burning phase begins and lasts until the He shell runs out of power because of the temperature drop caused by the closeness of the H-rich mantle. Fig. 2 illustrates (for the 3 $M_\odot$ case) how the T-RO relation changes during a TP duty cycle. The solid line refers to the pre-ignition phase while the dotted one shows the intershell structure a little bit after the quenching of the He convective shell, i.e. when the steady He burning starts. The short-dashed, dot-short dashed and double dot-short dashed lines show how the T-RO profile turns progressively back towards the accretion-controlled eigenstate as the He-burning shell quenches. The dotted line closely resembles a typical quiescent burning, as those shown in Fig. 1, demonstrating *in corpore vili* that the intershell structure naturally tends to a quiescent steady burning as it comes out of the thermal instability.

The huge amount of energy required to shift the intershell structure towards a steady burning condition is, per se, not sufficient to determine an alternation between the two burning shell. It is also necessary that this energy is injected very quickly in the star, so that all the region around the He ignition location expands and cools, in particular the H burning region. Such a quick energy release is guaranteed by the thermal instability first discovered and studied by Schwarzschild & Härm (1965): in fact, in the specific physical conditions in which He ignites (i.e. in a structure controlled by the accretion), the steepness of the 3α rate forces the growth of a thermal runaway that implies a rapid raise of the temperature and hence of the energy injection. The crucial role played by the steepness of the 3α cross section is evident by looking at Fig. 3. This figure shows the comparison between a reference run and a test one in which the cross section of the 3α was substituted by the $^{14}N(p,\gamma)$ one scaled down by a factor $\sim 2.5 \times 10^{12}$: in this way the fake 3α cross section equates the real one roughly at $T = 250$ MK. The starting model is a $3\,M_{\odot}$ (see above) that has already experienced roughly 30 TP. The black and grey lines in Fig. 3 show the run of $L_{3\alpha}$ for the standard and the fake cases, respectively. The effect of the steepness of the cross section of the 3α is dramatic: a shallower profile immediately kills the growth of any thermal instability and a quiescent double burning phase starts. This implies that the physical structure of the intershell readjusts on a shape typical of a quiescent steady nuclear burning: the thick solid line in Fig. 2 shows the T-RO profile corresponding to the steady He burning occurring in the test case. Such a profile is lower that in the TP case (dashed line in Fig. 2) because in a steady state condition the He shell must produce only 10% or so of the surface luminosity while in the standard case it must provide the full luminosity when the H shell is extinguished.

3. Conclusions

In this very short contribution we addressed an aspect of the evolution along the AGB not much discussed in the literature: the amount of energy released by the 3α process during a TP. Generally speaking, the existence of a thermally pulsing phase is based on the *recurrence* of these instabilities. The mere existence of an instability leading to a quick energy injection in the star does not guarantee such a recurrence because, if the H-burning shell were not extinguished by the thermal runaway, the He ignition would simply end up in a stable double burning shell configuration. Vice versa, the temperature-density profile determined by the accretion of He on top of the He core creates the right conditions for the existence of recurrent thermal pulses. In fact, on one side the steepness of the 3α process in this environment naturally leads to a thermal runaway and hence to a quick release of nuclear energy, but, on the other side, the transition occurring during a TP from an accretion-controlled structure to a burning-controlled profile requires the release of a huge amount of energy. It is the combination of these two cofactors that leads to the freezing of the H-burning shell first, to the extinguishing of the He-burning shell later and thence to the conditions for a further duty cycle to occur.

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