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Comments on the evolution of AGB stars

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Abstract. We describe in a brief form recent evolution calculations for low mass stars having solar-like initial composition up to their AGB phase. In this contribution we present the evolution of a $2\,M_\odot$ star which evolves through the core helium flash before reaching the AGB phase and compare it to the evolution of a $3\,M_\odot$ star which avoids the core Helium flash. In particular, we illustrate the effect of neutrino losses on the onset of thermal pulsation and the duration of the thermal pulses. Some characteristics of the core helium flash of the $2\,M_\odot$ star are presented.

Key words. Stars: AGB – Stars: evolution– Stars: nucleosynthesis

1. Introduction

Although the AGB phases of low and intermediate-mass stars are relatively short in astronomical standard, these phases are so important for the theory of stellar evolution and nucleosynthesis. The high luminosities of AGB stars help to better understand external galaxies with old populations. Another important aspect of AGB stars is related to the high mass loss they suffer which conduct them to planetary nebulae and finally to white dwarfs. This mass loss forms circumstellar envelopes which enable a link between stellar and interstellar media. It is also commonly accepted that the envelopes of AGB stars are the major factories of cosmic dust. AGB stars may have contributed to the formation of presolar grains which are well studied in the laboratory (e.g. Amari et al. 2001, and references therein). In particular, we are guided by the idea of studying the contribution of AGB stars to the interesting subgroup of presolar grains, called "A+B grains" showing peculiar isotopic ratios. These ratios may give insight in the internal structure of the AGB stars through the study of the physical conditions leading to their formation.

A large body of literature exists on the evolution of AGB stars which cannot be reviewed in the present short contribution. This is done in the nice review by Lattanzio & Wood (2004) where a comprehensive citing of recent works can be found.

2. Evolutionary results for the $2\,M_\odot$ and $3\,M_\odot$ stars

The stellar evolution code we have used to obtain the present results is a one-dimensional hydrodynamical code containing updated physical assumptions as described by The et al. (2000) and recently by El Eid et al. (2004). We have adopted initial solar-like compositions for the present stars. For the mass loss by stellar wind, we used the semi-empirical rates by de Jager et al. (1988) in the

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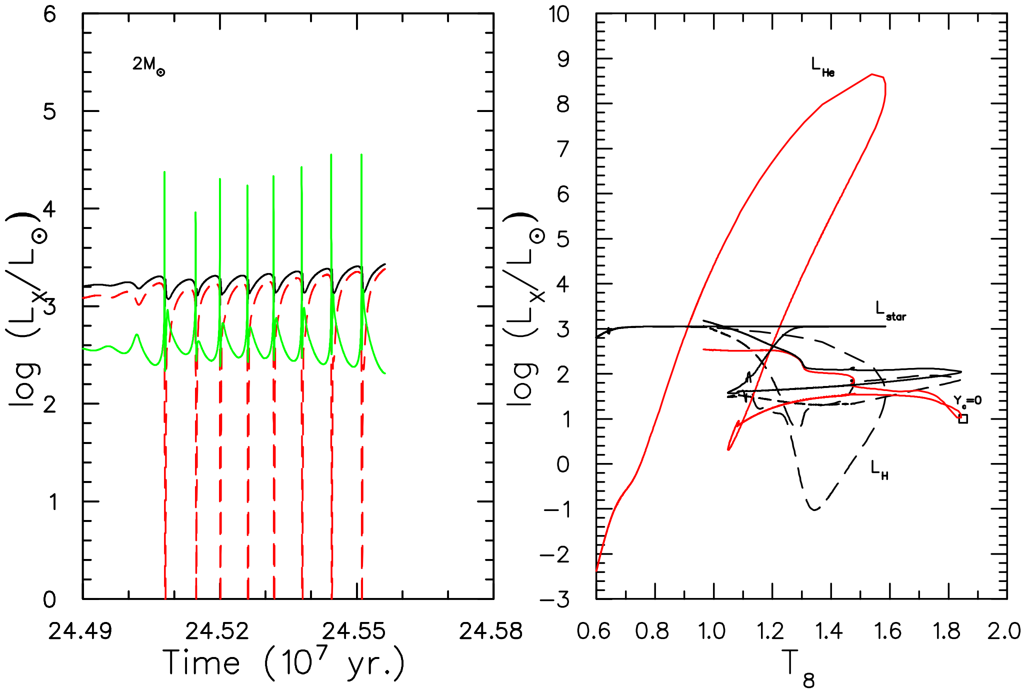

Fig. 1. The evolution of a $2\,M_\odot$ star through the core helium flash and the first 8 thermal pulses on the AGB. Left panel shows 8 thermal pulsations of this star. The time scale on the abscissa is taken from onset of core helium burning. Right panel shows the luminosity of the star L_{star} together with L_H of the hydrogen shell and L_{He} of the core helium burning as a function central temperature T_8 (in units of 10^8 K). Notice the sharp increase of the L_{He} starting at $T_8 = 0.8$ indicating the helium flash. This luminosity achieves a amazing peak value of about $10^9\ L_\odot$ without having any direct effect on the star's luminosity (see text for details).

case of the $3\,M_\odot$ star. However, for the $2\,M_\odot$ star, we adopted the Reimers's (see Blöcker 1995) semi-empirical rate according to to the relation:

$$(dM/dt)_R = 4 \times 10^{-13}\,\eta\,L\,R/M \quad (1)$$

in $M_\odot$/yr and where L, R and M are relative to the solar values. We have taken $\eta = 0.50$ in our case. On the AGB, mass loss should increase. One way to do so is according to the following semi-empirical formula:

$$dM/dt = 4.83 \times 10^{-9}\,M^{-2.1}L^{2.7}\,(dM/dt)_R \quad (2)$$

where L and M are relative to the solar values. This second relation has been obtained by Bowen (1988) for Mira-like variables and should account for the increased mass loss during the AGB phases. It is used (see Blöcker 1995) under the condition that the period of the fundamental pulsation mode exceeds 100 days, where this period is approximated by:

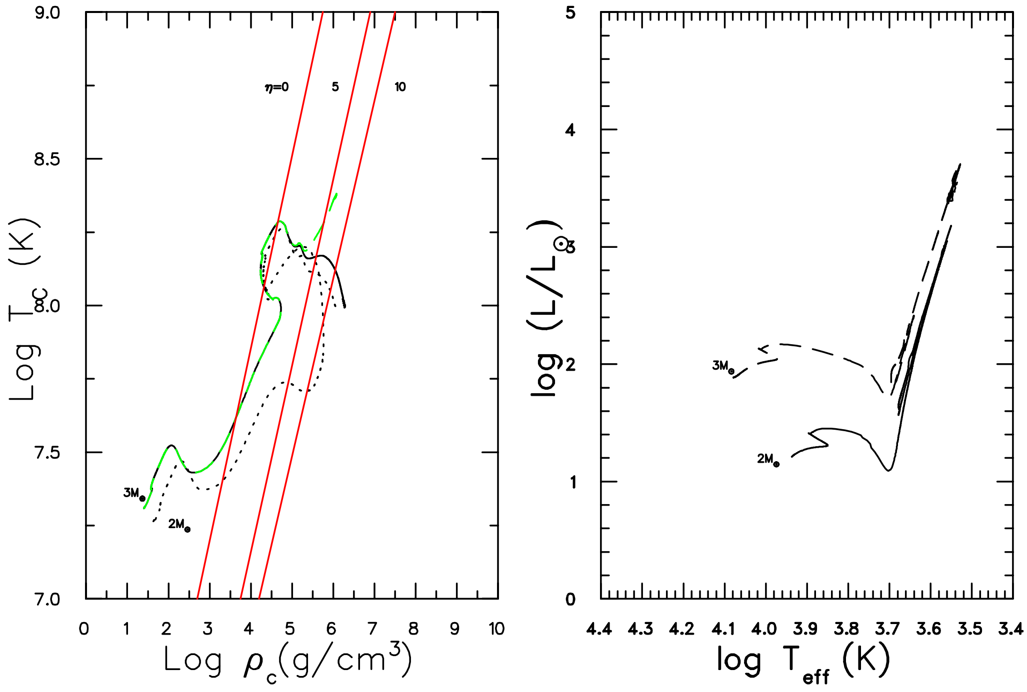

Fig. 2. Left panel: Evolution of the 2 and 3 $M_\odot$ stars in the T_c-ρ_c plane where lines of constant degeneracy parameter η indicating the degree of degeneracy of the electrons. The higher density encountered in the 2 $M_\odot$ explains its central evolution beyond η = 10 where it experiences a helium flash. The central evolution of the 3 $M_\odot$ star is shown in case of neutrino losses included (solid line) or omitted (dashed line) (see text for details). Right panel shows the HR diagram for the these stars as they evolved to the AGB phase.

$$\log(P/d) = -1.92 - 0.73 \log(M) + 1.68 \log(R) \quad (3)$$

where L and R are relative to the solar values. The coupling of the second mass loss rate to the period of 100 days and above means that this increased mass loss will be found only after several thermal pulsation. In our case the period reaches 88 days after 8 thermal pulsations in the 2 $M_\odot$ star. We emphasize that our choice of the mass loss rates will be certainly subject to further revision owing to the lack of a basic theory of mass loss. Our aim is to have a variety of stellar models on the AGB for different masses for testing not only mass loss but also the effect of convective mixing on their evolution and for the study of the nucleosynthesis during these interesting evolutionary phases of stars.

In the following, we describe some of the results we have obtained so far for the 2 and 3 $M_\odot$ stars. The 2 $M_\odot$ star belongs to the subgroup of low mass stars which experience core helium flash while attempting to ignite helium. This is a thermal runaway and is a consequence of the instability of nuclear burning in strongly degenerate region. The character-

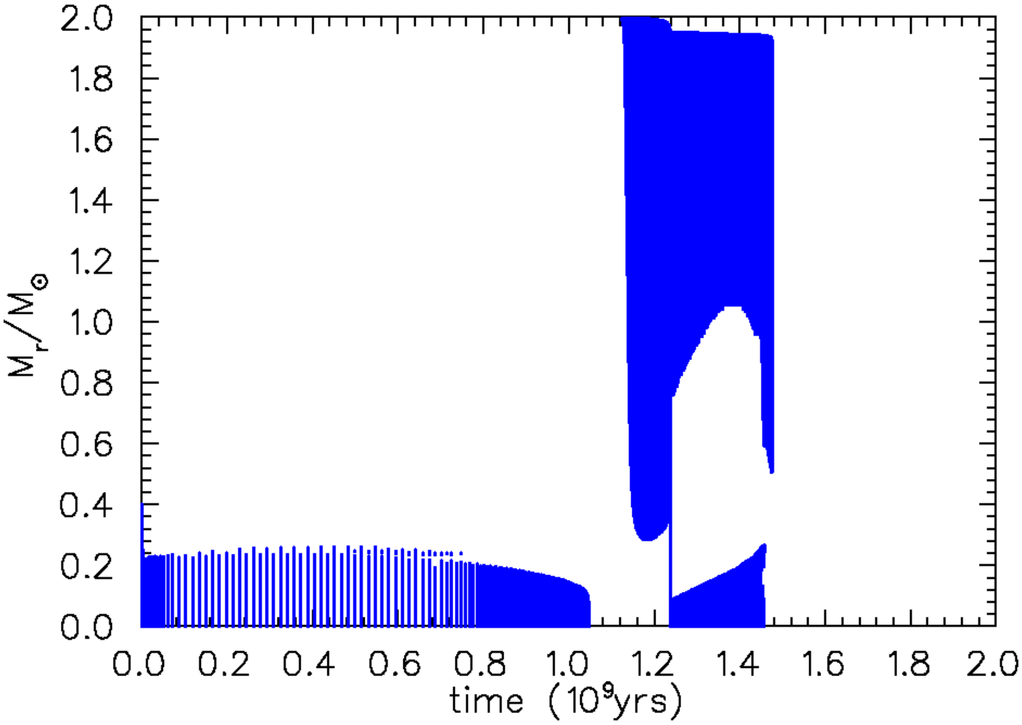

Fig. 3. Evolution of the convective (dark areas) and the radiative structures with time for the 2 $M_\odot$ star of initial metallicity Z= 0.02. This evolution is from the main sequence to the AGB phase, see text.

istic of the helium flash is displayed in Fig. 1 (right panel) and Fig. 2 (left panel). In Fig. 1 (right panel), the star's luminosity L_{star} is shown together with the luminosities of the hydrogen shell L_H and the helium burning L_{He}. The onset of the helium flash is marked by the strong increase of L_{He} when the central temperature approaches $T_8 = 0.8$. There is an enormous power released during this phase such that L_{He} reaches a peak value close to 10^9 $L_\odot$. Nevertheless, the star's luminosity (L_{star}, Fig. 1, right panel) remains unaffected. This is because the power released by the helium flash is entirely used to expand the star such that the hydrogen shell is weakened which leads to the reduction of star's luminosity seen in Fig. 1 (left panel) after the flash. The evolution of the 2 $M_\odot$ star in the $T_c - \rho_c$ plane is shown in Fig. 2 (left panel) together with evolution of the 3 $M_\odot$ (discussed below). The 2 $M_\odot$ star evolves toward higher densities beyond the line marked by the degeneracy parameter $\eta = 10$ indicating strong degeneracy conditions responsible for the helium flash described above. The ensuing evolution at almost constant density characterizes the thermal runaway such that stable helium burning can only occur near the $\eta = 0$ line. The core helium burning ends where the inserted square is marked by $Y_c = 0$ in Fig. 1 (right panel). Fig. 1 (left panel) shows the first 8 pulses of the 2 $M_\odot$ star after it has evolved through the helium flash. These pulses have

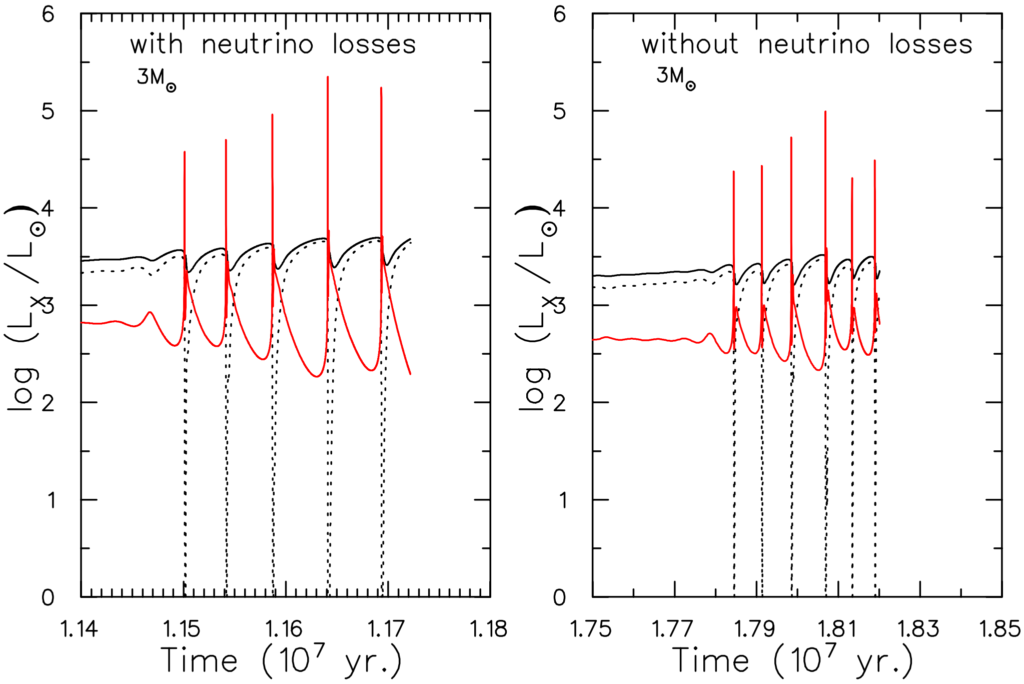

Fig. 4. Evolution of a 3 $M_\odot$ star through the first 5 or 6 thermal pulses on the AGB. The dotted lines display the luminosity of the hydrogen shell, the solid lines with the spikes represent the luminosity of the helium shell and the other solid lines shows the star's luminosity. Note that in the right panel, the energy losses due to neutrino processes were artificially suppressed. The inter-pulse timescale is strongly affected by neutrino losses.

inter-pulse durations ranging between 5.0 to 7.5×10^4 yr. The first pulse begins at the time of about 2.45×10^8 yr after begin of core helium burning. At the time of the first pulse the mass of the star has been reduced by the mass loss we have used to 1.897 $M_\odot$.

In Fig. 2 (right panel), the evolution of the 2 $M_\odot$ is shown in the HR diagram and is compared to the track of the 3 $M_\odot$. In Fig. 3, we show the evolution of the convective and radiative structures with time for the 2 $M_\odot$ star. Seen is the convective core hydrogen burning which lasts up to 1.0494×10^9 yr followed by a long contraction phase (1.815×10^8 yr). The spike near to 1.2×10^9 yr indicates the core helium flash. After that helium burning is stabilized and proceeds in a convective core with a maximum mass about 0.24 $M_\odot$. The duration of core helium burning is 2.24×10^8 yr. In Fig.3, one also sees the outer convective envelope and how much mass the star had lost (about 0.10 $M_\odot$) till 8 thermal pulses. Some results of the evolution of the 3 $M_\odot$ star are shown in Figs. 2 and 4. While we have been testing the neutrino energy losses according to the compilation by Itoh et al. (1996) we evolved the 3 $M_\odot$ star without including the neutrino energy losses. The results of this experiment are really remarkable at least pedagogically. The evolution of the center of this star seen in Fig.

2 (left panel) indicates clearly the cooling effect of neutrinos leading to a decrease of the central temperature instead of increasing when neutrino energy losses are omitted. Another effect is the remarkably different time scales of the early AGB phase till the onset of the first pulse: with neutrino losses this time scale is shorter by about 6.35×10^6 yr. Also the interpulse duration is appreciably shorter (by more than 30%) when the neutrino energy losses are included. Finally neglecting the effect of neutrinos on this phase of evolution reduce the luminosity of the helium shell during the thermal pulse (compare right and left panels in Fig. 4).

The core hydrogen burning of the $3\,M_\odot$ star lasts for 3.15621×10^8 yr. Its contraction phase toward He-ignition takes 1.67×10^7 yr and its core helium burning lasts for 1.87×10^8 yr. It is interesting to note that the mass of the hydrogen-exhausted core (M_H) we found at the onset of the first thermal pulse is in complete agreement with the values obtained recently by Stancliffe (2005) in the case of the $3\,M_\odot$. For this star, Stancliffe's value is $0.5635\,M_\odot$, while our value is $0.564\,M_\odot$. For the $2\,M_\odot$ star, we have different results: Stancliffe's value is $0.5679\,M_\odot$ while our value is $0.513\,M_\odot$. It is astonishing that the Stancliffe's value for the $2\,M_\odot$ star is larger than for the $3\,M_\odot$ star. We also note that we have evolved the $2\,M_\odot$ star through the helium flash while Stancliffe did not. Detailed comparison of our calculations also with other workers in the field will be done in a forthcoming paper.

3. Outreach

We have presented only few results from our current calculations for AGB stars. A de tailed discussion will be published elsewhere. It would be interesting to see how far the one-dimensional hydrodynamical calculations we have outlined for the $2\,M_\odot$ star agrees with the fancy three-dimensional simulation briefly described in the meeting by J.L. Lattanzio and collaborators.

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