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LETTER

Letter to the Editor

A theoretical model for episodic mass-loss producing detached shells around bright carbon stars

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Abstract. We present stellar evolution models of the final AGB phase, in which the star undergoes heavy and optically thick mass-loss ("superwind" phase). Our computations are based on consistent, pulsating wind models for carbon-rich stars and include a detailed treatment of dust formation, radiative transfer and wind acceleration (Fleischer et al. 1992). For a specific mass range, around 1.2 $M_\odot$ stellar mass at the foot-AGB and only about 0.2 $M_\odot$ wide, we find particularly pronounced episodic mass-loss which is consistent with all properties of the detached CO shells found by Olofsson et al. (1990, 1993, 1996) around bright carbon stars: kinematic ages of 1 to 2 $\times 10^4$yrs, masses of several 0.01 $M_\odot$, and a mass-loss duration of less than several thousand years.

The physics, micro-physics, and chemistry of our dust-induced superwind is essential for understanding such details of the final stellar mass-loss history. Unlike other superwind models, our mass-loss rate depends very sensitively on the stellar temperature – about $\propto T_{\rm eff}^{-8}$ – and our models require a minimum luminosity to be surmounted. Together, that yields a much pronounced mass-loss variation with the late thermal pulses. In particular, our models suggest the formation of CO shells in the final 2 to 6 $\times 10^4$yrs on the tip-AGB – if the stellar luminosity is close to the critical (Eddington–like) luminosity log L_c (around 3.5 to 3.7, depending on $T_{\rm eff}$), while the star has only $\lesssim 0.2 M_\odot$ left to lose towards the exposure of its hot core.

Key words: stars: carbon – stars: circumstellar matter – stars: evolution – stars: interiors – stars: late-type – stars: mass loss

1. Introduction

The term "superwind" was coined by Renzini (1981), referring to the heavy tip-AGB mass-loss ($\gtrsim 10^{-5} M_\odot$yr^{-1}), which is required to form a planetary nebula (PN) of typically a few tenths of a solar mass (Peimbert 1981) within several 10^4yrs, and which develop from a long but much less massive AGB mass-loss history (e.g., Lafon & Berruyer 1991). Such a picture is in good agreement with the findings of cool, dust- and CO-rich circumstellar envelopes (CSE) around PN's (Kwok 1981) and the mass-loss rates of about 10^{-4} $M_\odot$yr^{-1} as modeled on LPV (long period variable) observations (e.g., Knapp & Morris 1985, Winters et al. 1997).

The superwind is a dominant factor in tip-AGB evolution (illustrated by Fig. 1), while the mass-loss rate itself is critically dependent on the actual stellar parameters. Hence, mass-loss and final stellar evolution have to be computed hand in hand. Recent contributions to this problem have been published by Vassiliadis & Wood (1993) and Blöcker (1995). Both approaches use a Bowen-type wind-model (Bowen 1988) with a period – mass-loss relationship, i.e., the mass-loss rate depends strongly on the surface gravity g. That leads to a gradual but strong enhancement of the tip-AGB mass-loss, in good agreement with observational evidence. However, those simple wind-models fail to treat in detail the important problem of dust-formation with its complex, highly temperature- and density-dependent physics and chemistry.

While the general picture of PN formation is now certainly understood, well observed details of that process still await an explanation by more detailed models of the tip-AGB evolution and superwind mass-loss: For a few carbon stars (3 in a sample of 65) Olofsson et al. (1990, 1993, 1996) found thin, detached CO shells with kinematic ages of 3 to 13 thousand years and masses of 0.4 to 5$\cdot 10^{-2}$ $M_\odot$, reminiscent of very short (less than several thousand years) episodes of a superwind which are contrasting the presently two orders of magnitude less dense winds of those objects. The authors suggest thermal pulses as a possible reason for these abrupt and strong mass-loss fluctuations, but all previous theoretical work rather suggests an only gradual and less strong mass-loss modulation (e.g., Vassiliadis & Wood 1993).

2. A new approach to the 'superwind' problem

A much different approach to tip-AGB mass-loss is provided by a consistent treatment of the dust-induced wind generation, including a detailed description of hydrodynamics, thermodynamics, chemistry, radiative transfer, dust formation and growth (see Sedlmayr 1994, Sedlmayr &

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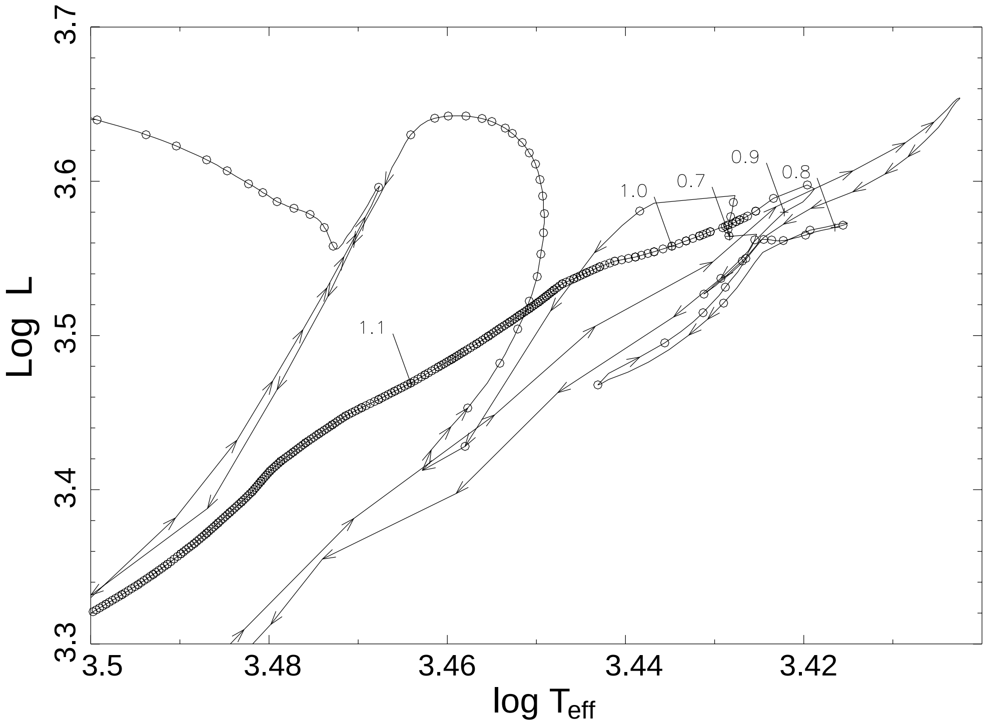

Fig. 1. The final, tip-AGB evolution of a star with an initial AGB mass (at the begin of He burning) of 1.25 $M_\odot$ and about solar composition. Only the last thermal pulses are shown. Circles mark time-steps of 3000 yrs, numbers mark actual masses.

Winters 1997, for recent reviews). Based on such detailed computations, Fleischer et al. (1992) have introduced consistent dynamical wind models for pulsating, C-rich AGB stars. These are in good agreement with observed carbon star mass-losses (Le Bertre & Winters 1998). From a grid of 48 such models, Arndt et al. (1997) derived an approximative mass-loss formula for the tip-AGB region of the HR diagram (M, L in solar units): $\log \dot{M} = 17.16 - 8.26 \cdot \log T_{\rm eff}/K + 1.53 \cdot \log L - 2.88 \cdot \log M$

The resulting strong inverse dependence on stellar mass and the magnitude of the mass-loss rates qualify for a superwind. Furthermore, the mass-loss depends very sensitively on the stellar temperature, which originates in the strong temperature dependence of the micro-physics and chemistry of the dust formation process. Since the mass loss is driven by radiation pressure on dust, the models require a critical minimum luminosity to be surmounted in order to drive the wind (see e.g. Sedlmayr & Winters 1997). The exact value of this *Eddington luminosity* depends on the actual dust opacity and thus, via the dust formation process, on $T_{\rm eff}$ and is typically of the order of log $L_c \approx 3.7$ for log $T_{\rm eff} = 3.5$ and 1 $M_\odot$.

In this paper, we present first results from applying this pulsating, dust-induced superwind to tip-AGB stellar evolution (see Fig. 1), which results in episodic mass-loss events, capable of forming the observed detached CO shells around bright carbon stars.

We use the most recent version of an evolution code developed by Eggleton (1971, 1972, and see Pols et al. 1995 and references therein), with a parameterized convective mixing that has been well tested by a variety of empirical methods (Schröder et al. 1997, Pols et al. 1997, Pols et al. 1998) which reach into the AGB. However, as with most contemporary evolutionary codes, tip-AGB effective temperatures turn out to be higher than their empirically derived values when a fixed convective mixing length ($\alpha = 2.0$, in units of the pressure scale height) is used. The Eggleton code requires a gradually decreasing α on the AGB, reaching 1.5 at $\log g$ (cgs) $= -1$ as parameterized by α = 2.0 + $0.17 \cdot (\log g/g_\odot + 2.5)$. We thus compensate, roughly but economically, for several common short-comings of the code which affect $T_{\rm eff}$, such as the mixing length theory itself or incomplete opacities.

The self-adjusting mesh of the Eggleton code easily accepts a significant mass-loss as part of the boundary condition. It is designed to be very robust and economic. Consequently, it is capable of using fairly large timesteps and ignores thermal pulses until the mass-loss becomes significant for stellar evolution (i.e., exceeding $\approx 10^{-6}\ M_\odot {\rm yr}^{-1}$). By a superficial comparison to other computations (e.g., Vassiliadis & Wood 1993), the timescale we obtain for those final thermal pulses seems to be shorter. However, at the very tip-AGB, the thermal pulse cycle time does decrease significantly – see, e.g., Fig. 1 of Wagenhuber & Weiss (1994).

To provide a realistic mass-loss history, we use the empirical mass-loss formula of Reimers (1975) for the pre-AGB and core He-burning evolution, with $\eta = 4 \cdot 10^{-13}$, and further on the AGB the one of de Jager et al. (1988). Finally, the superwind sets in on the tip-AGB, between log L = 3.5 and 3.6 for the models shown here, and its mass-loss rate is computed according to Arndt et al. (1997).

3. Episodic mass-loss at the tip-AGB

As representative results we show the tip-AGB mass-loss histories of stellar models with an initial AGB mass of 1.15

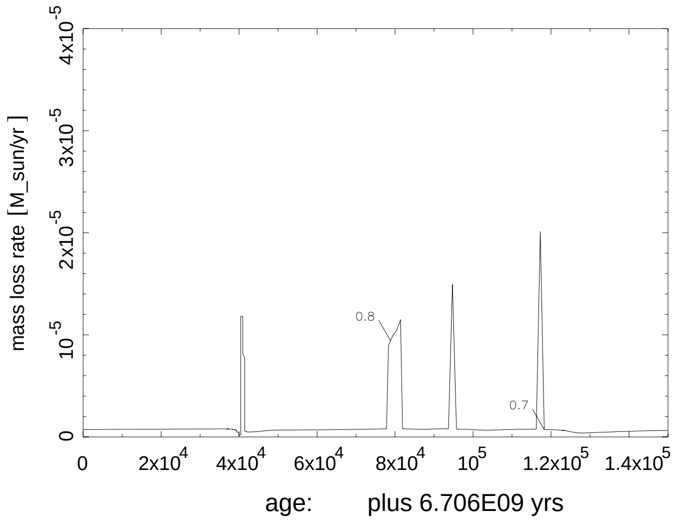

Fig. 2. The final, tip-AGB mass-loss history for a 1.15 $M_\odot$ initial AGB mass star. Actual masses are marked by numbers. When such a carbon star reaches the critical luminosity on the tip-AGB, short (episodic) bursts of superwind occur which result in a detached shell, each.

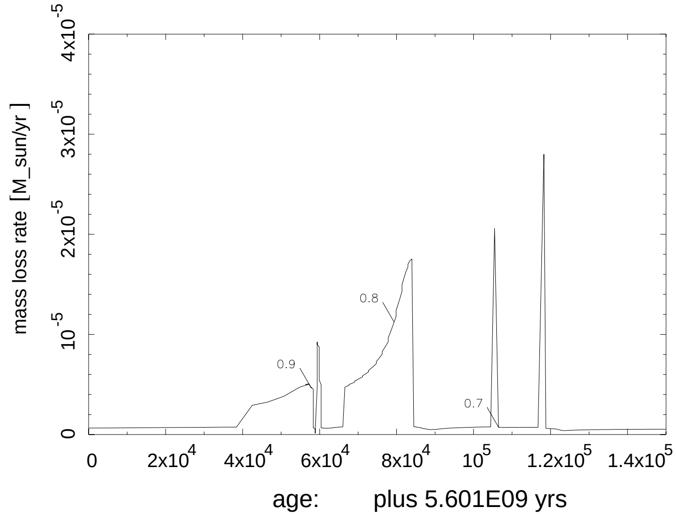

Fig. 3. The final, tip-AGB mass-loss history for the 1.25 $M_\odot$ initial AGB mass star shown in Fig. 1. Numbers mark actual masses. A superwind phase is preceeded and followed by strong mass-loss fluctuations.

$M_\odot$ (Fig. 2), 1.25 $M_\odot$ (Fig. 3, compare to Fig. 1) and 1.4 $M_\odot$ (Fig. 4), each with approximately solar chemical composition: $X = 0.70$, $Y = 0.28$, $Z = 0.02$. The actual masses are indicated in each plot.

On the AGB, prior to the final $\approx 10^5$ yrs and the onset of the superwind, about 0.3 $M_\odot$ are lost, leaving yet another 0.2 to 0.4 $M_\odot$ to be removed by the superwind. The physics, microphysics and chemistry of the pulsating, dust-induced superwind play a very important rôle for the details of this picture – they mainly yield a very strong dependence of the mass-loss on stellar temperature and, especially near L_c, on stellar luminosity. Therefore, pronounced CSE structure can be formed with the late thermal pulses:

During the actual thermal pulse, we find the mass-loss dropping, then sharply rising again, by 1 to 2 orders of magnitude, on the ultra-short time-scale of 10^2yrs. That is in excellent agreement with recent observations of Hashimoto et al. (1998).

After a thermal pulse, the mass-loss peaks during the time of enhanced luminosity and lowered effective temperature – both caused by the delayed release of the pulse energy which has been stored in the stellar envelope. With decreasing $M_{\rm ini}$ and thus envelope mass, this mass-loss variation becomes more pronounced (see also Vassiliadis & Wood 1993). If, in addition, the stellar luminosity is close to L_c (in the last few 10^4yrs on the tip-AGB), while there is only 0.2 $M_\odot$ left to lose towards the exposure of the core, we obtain a brief ($\lesssim 3000$ years) burst of heavy mass-loss (see Fig. 2 and 3). It is ended by the quick response of the low-mass stellar envelope and its thin H-burning shell, i.e., by reduced L and increased $T_{\rm eff}$.

During a period of less strong mass-loss, such a star should then regain visibility and feature a thin shell of several 10^{-2} $M_\odot$ and a kinematic age of the order of 10^4yrs – in strikingly good agreement with the findings of Olofsson et al. (1993, 1996).

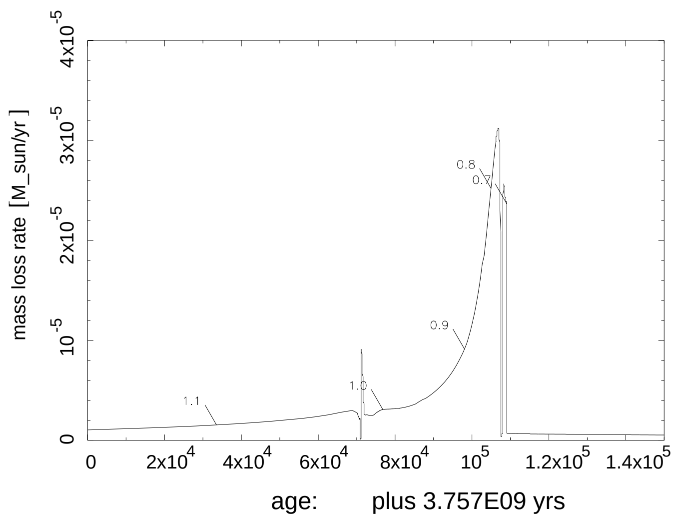

Fig. 4. The final, tip-AGB mass-loss history for a 1.4 $M_\odot$ initial AGB mass star. Numbers mark actual masses. With larger stellar mass, mass-loss fluctuations in the superwind phase decrease.

Our superwind models yield wind and shell velocities which both are in the range of 10 to 20 km/s, gradually increasing with the actual C/O ratio. That is well within the range of measured CO shell velocities, i.e., 13 to 20 km/s as reported by Olofsson et al. (1996).

The evolutionary time-scales and thus the expected ratio of bright carbon stars with a detached shell over those without (seen during their pre-superwind phase, which lasts about several 10^5 years) are roughly 1 to 10. Considering furthermore a selection factor of about 2-3 according to the restricted mass-range of such objects, we arrive at the numbers found by Olofsson et al. (1990) – 3 carbon stars with a detached CO shell in a sample of 65.

Our models with less than 1.1 $M_\odot$ (stellar mass on the foot of the AGB) do not reach the superwind phase – their cores become exposed before sufficiently high luminosities are reached. For 1.4 $M_\odot$ and more, tip-AGB luminosities exceed L_c sufficiently and the mass-loss variations become less extreme. Our respective models end the superwind phase without detached shells being formed (Fig. 4). That constrains the initial stellar masses of carbon stars with detached shells very well. Their actual masses are also supposed to be in a narrow range around 0.7 to 0.8 $M_\odot$.

4. Discussion

The results presented here agree well with the general picture of the final stages of stellar evolution and the observed superwinds. During the superwind, between 0.2 and 0.4 $M_\odot$ are lost by stars of initially 1.3 to 1.5 $M_\odot$ (that is about 1.2 to 1.4 $M_\odot$ at the foot-AGB) within 2 to 4$\cdot 10^4$yrs – in good agreement with the rates (several 10^{-5} $M_\odot$yr^{-1}), kinematic ages (several 10^4yrs) and masses (several 0.1 $M_\odot$) observed with the optically thick CSE of some LPV. At the very end of stellar evolution and mass-loss our models have a final mass of 0.58 $M_\odot$. That is in good agreement with the relation of Weidemann (1987).

We therefore believe that our results, although preliminary, already give a qualitatively correct understanding of the final $\approx 10^5$ yrs of typical AGB stars.

The complexity of the problem of tip-AGB stellar evolution in the presence of heavy mass-loss leaves, however, several aspects to be improved by future work. The main points concern upgrading the opacities and critical tests of the tip-AGB effective temperatures. Nevertheless, the superwind itself would not be much different if the critical tip-AGB HR diagram region may be, e.g., reached a bit earlier – only the core mass and final stellar mass would be slightly smaller. Finally, a more complete treatment of the convective mixing history, i.e., including the dredge-up's of the earlier thermal pulses, would yield the whole change of the chemical surface abundances such as the C/O ratio. That would help to better define the onset of the C-rich superwind on the AGB. Fortunately, the mass-loss rate itself does not depend much on the actual C/O ratio (see Arndt et al. 1997). A more detailed discussion will be subject to a future publication.

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