Asymptotic Giant Branch Stars
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The final 10^5 years of stellar AGB evolution in the presence of a pulsating, dust-induced "superwind"

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Abstract. We have computed mass-loss histories and tip-AGB stellar evolution models in the presence of a dust-induced, carbon-rich "superwind", in the initial mass-range of 1.1 to about 2.5 solar masses and for nearly solar composition (X=0.28, Y=0.70, Z=0.02). Consistent, actual mass-loss rates are used in each time-step, based on pulsating and "dust-driven" stellar wind models for carbon-rich stars (Fleischer et al. 1992) which include a detailed treatment of dust-formation, radiative transfer and wind acceleration. Our tip-AGB mass-loss rates reach about $4 \cdot 10^{-5} M_{\odot} \mathrm{yr}^{-1}$ and become an influencial factor of stellar evolution.

Heavy outflows of 0.3 to 0.6 $M_{\odot}$ within only 2 to $3 \cdot 10^4$ yrs, exactly as required for PN-formation, occur with tip-AGB models of an initial stellar mass $M_i \gtrsim 1.3 M_{\odot}$. The mass-loss of our "superwind" varies strongly with effective temperature ($\dot{M} \propto T_{\mathrm{eff}}^{-8}$, see Arndt et al. 1997), reflecting the temperature-sensitive micro-physics and chemistry of dust-formation and radiative transfer on a macroscopic scale. Furthermore, a thermal pulse leads to a very short (100 to 200 yrs) interruption of the "superwind" of these models.

For $M_i \lesssim 1.1 M_{\odot}$, our evolution models fail to reach the (Eddington-like) critical luminosity L_c required by the radiatively driven wind models, while for the (initial) mass-range in-between, with the tip-AGB luminosity L_{tAGB} near L_c, thermal pulses drive bursts of "superwind", which could explain the outer shells found with some PN's. In particular, a burst with a duration of only 800 yrs and a mass-loss of about 0.03 $M_{\odot}$, occurs right after the last AGB thermal pulse of a model with $M_i \approx 1.1 M_{\odot}$. There is excellent agreement with the thin CO shells found by Olofsson et al. (e.g., 1990, 1998) around some Mira stars.

1. Introduction

Theoretical models of tip-AGB mass-loss are of considerable interest in several respect: from the stellar evolution point of view, for the understanding of the structure of circumstellar envelopes (CSE) and planetary nebulae (PN), and for the chemical evolution of the Galaxy and galaxies in general.

The term "superwind" was coined by Renzini (1981), referring to the heavy tip-AGB mass-loss ($\gtrsim 10^{-5} M_{\odot} \mathrm{yr}^{-1}$), which is required to form a PN of typically a few tenths of a solar mass within several 10^4yrs. It is supposed to develop

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rather gradually, by an accelerating increase of mass loss, from a long history of less massive AGB mass-loss. Such a picture is in good agreement with the findings of cool, dust- and CO-rich CSE's around PN's (Kwok 1981) and the mass-loss rates of about 10^{-4} $M_{\odot}\mathrm{yr}^{-1}$ as modeled on LPV (long period variable) observations.

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. We may remind of the well-known outer shells seen around PN's in deep exposures. A probably related phenomenon seem to be the thin, detached CO shells found by Olofsson et al. (e.g., 1990, 1998) around a few carbon stars, having kinematic ages of 3 to 13 thousand years and masses of 0.4 to $5{\cdot}10^{-2}$ $M_{\odot}$. These shells suggest very short (about a thousand years or less) episodes of strongly (by 2 orders of magnitude) increased mass-loss.

Because of a significant interaction between the stellar structure and a heavy mass-loss, both have to be computed hand in hand on the tip-AGB. Earlier approaches have been published by, e.g., Vassiliadis & Wood (1993) and Blöcker (1995), which both 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. Those simple wind-models fail, however, to treat the important problem of dust-formation, with its complex and highly temperature- and density-dependent physics and chemistry, in sufficient detail.

A much different approach to tip-AGB mass-loss has been achieved by a consistent treatment of a dust-induced wind generation – including the detailed description of hydrodynamics, thermodynamics, chemistry, radiative transfer, dust formation and growth (see Sedlmayr 1994 for a review). Based on such extensive computations, Fleischer et al. (1992) have introduced consistent dynamical wind models for pulsating, C-rich AGB stars.

2. The evolution code and our approach of the "superwind" problem

We use the most recent version of an evolution code as described by Pols et al. (e.g., 1995, 1998), which is based on the original evolution program of Eggleton (1971, 1972). The essential features, in which this very economic and robust code differs from other evolution programs, are: (1) the use of a self-adaptive, non-Lagrangian mesh (only 200 mesh points required), (2) the treatment of both convective and semi-convective mixing as a diffusion process with a diffusion rate adopted as a function of $(\nabla_{\mathrm{rad}} - \nabla_{\mathrm{ad}})$ (otherwise, standard mixing length theory is used) and (3) the simultaneous and implicit solution of both the stellar structure equations and the diffusion equations for the chemical composition. A trade-off for the fastness of the code is, however, that surface abundance changes through dredge-up's are, in the present version, not computable and thermal pulses are picked up only later on the AGB as with other codes.

We here use the same set of parameters as discussed and recommended by Schröder (1998), and which are the result of a variety of critical tests by empirical methods.

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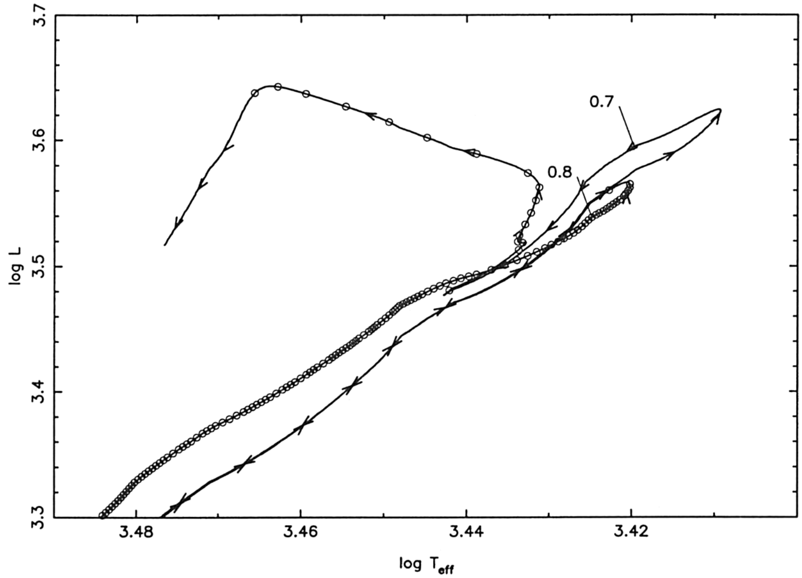

Figure 1. Tip-AGB evolution for $M_i = 1.10 M_\odot$ and solar composition. Only the last AGB thermal pulse is shown. Circles mark timesteps of 5000 yrs, arrows indicate direction of fast evolution and numbers mark the actual mass.

To incorporate realistic superwind mass-loss rates, we use analytic representations of $\dot{M}$ as obtained from a large number of detailed wind-model computations (after Fleischer et al. 1992). A minimum outward directed force is required to drive this type of wind, which translates into a critical *Eddington*-like luminosity.

Furthermore, there is a very strong dependence of $\dot{M}$ on effective temperature which has its origin in the temperature-critical micro-physics and chemistry of the dust formation process (i.e., the grain nucleation rate) and is a characteristic property which we expect from any truly detailed model of a dust-induced wind.

As it turns out, these models lead to a rapidly increasing tip-AGB mass loss, with a magnitude that qualifies for a superwind. From a grid of 48 detailed wind models, Arndt et al. (1997) derived an approximative mass-loss formula for the tip-AGB region of the HR diagram which we have adopted for our computations: $\log \dot{M} = 17.16 - 8.26 \cdot \log T_{\text{eff}}/K + 1.53 \cdot \log L - 2.88 \cdot \log M$

Our first results have been published by Schröder et al. (1998). This work now incorporates several improvements:

(1) A very well defined *Eddington-like* luminosity L_c and its variation with effective temperature T_{eff}. For that purpose, we computed a number of specific wind models in the critical parameter space and find, e.g., $L_c = 5\,500 L_\odot \cdot M_*/M_\odot$ at $T_{\text{eff}} = 2\,600\,\text{K}$, or $9\,500 L_\odot \cdot M_*/M_\odot$ at $T_{\text{eff}} = 3\,000\,\text{K}$, respectively.

(2) A realistic, gradual transition of the mass-loss rate at the onset of the "superwind". When L_{tAGB} approaches L_c, there is a ramp with a width of 0.04 in $\log L$, which matches the actual sensitivity of our wind models to small luminosity differences near L_c.

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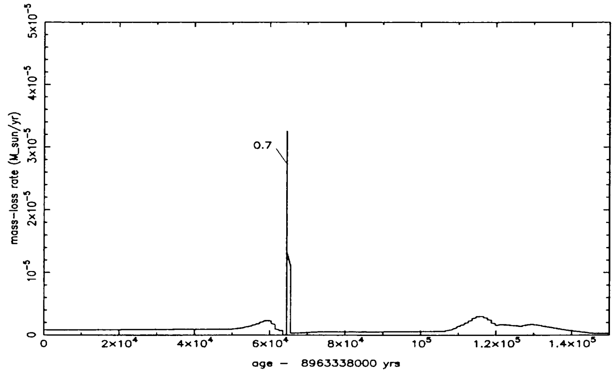

Figure 2. Tip-AGB mass-loss history for the evolution model ($M_i = 1.10 M_\odot$) shown in Fig. 1. Actual masses are marked by numbers. When such a star briefly reaches the critical luminosity on the tip-AGB with its last thermal pulse on the AGB, a short (about 800 yrs) burst of superwind occurs.

(3) A realistic, well constrained pre-AGB mass-loss: a critical figure is the minimum initial mass M_i of stars which, after their mass-losses on the giant branch (GB), can just reach their central He-burning – i.e. 0.95 $M_\odot$ with our parameterization. In particular, we use the "Reimers formula" (Reimers 1975) with $\eta_{\mathrm{RML}} = 2 \cdot 10^{-13}$.

(4) Consistently reduced time-steps, when larger mass-loss rates occur, to keep the mass lost in every time-step well below $10^{-3} M_\odot$, and to avoid any artificial reaction of the stellar model, even under extreme conditions.

3. Results: short bursts of heavy mass-loss and regular "superwinds"

When the tip-AGB luminosity L_{tAGB} reaches only just L_c, as with masses $\leq 1.3\, M_\odot$, then the stellar model is driven into and out of the "superwind" mass-loss by its last one or two thermal pulses on the AGB. The response of the then very thin ($\lesssim 0.2\, M_\odot$) stellar shell to thermal pulses, especially in luminosity, is very pronounced, and both gravity and T_{eff} are very low.

With the improvements mentioned above, we here can draw an accurate picture of the dramatic changes of mass-loss in this range of initial stellar mass: The lowest mass model ($M_i = 1.1\, M_\odot$), which reaches L_c only marginally, is plotted in Fig. 1 – its mass-loss history is plotted in Fig. 2. An isolated superwind burst is driven by the steep but very short (800 yrs) luminosity peak immediately after the last thermal pulse on the tip-AGB, during the re-ignition of the H-burning shell. The resulting superwind burst removes 0.025 $M_\odot$, at a rate of $3 \cdot 10^{-5} M_\odot \mathrm{yr}^{-1}$. That meets exactly the mass-loss requirements of the thin detached shells found in CO observations by Olofsson et al. (eg., 1990, 1998).

Models with slightly increased M_i already probe L_c more easily, resulting in several bursts of superwind with a typical duration of Δt of several thousand years, as with the mass-loss history of a star with $M_i \approx 1.2\, M_\odot$.

By contrast, from $M_i \approx 1.3\, M_\odot$ onwards, tip-AGB luminosities consistently reach beyond L_c and all our evolution models show a fairly similar, regular

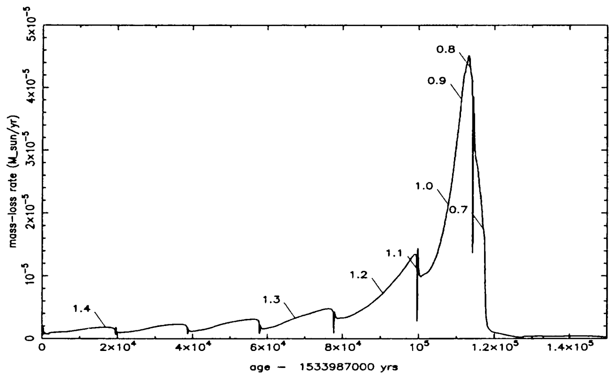

Figure 3. Tip-AGB mass-loss of an evolution model with $M_i = 2.25 M_\odot$, showing a typical "superwind" history.

superwind mass-loss record during their final 2 to $3 \cdot 10^4$ years (see Fig. 3). The superwind duration and the total mass loss in that phase varies surprisingly little with M_i: from about 0.3 $M_\odot$ with $M_i = 1.3\, M_\odot$ to 0.5 $M_\odot$ with $M_i = 2.25 M_\odot$.

During the brief drop of luminosity during each thermal pulse, combined with an increased $T_{\rm eff}$, for only 100 to 200 years, the mass-loss rate is reduced by 1 to 2 orders of magnitude. That strong contrast is the result of both the strong luminosity and temperature sensitivity of the dust-induced mass-loss. Again there is matching evidence from detached shell observations, which suggest mass-loss interruptions at similar time scales – see, e.g., Hashimoto et al. (1998).

The sensitive dependence of $\dot{M}$ on $T_{\rm eff}$ becomes noticeable in the mass-loss history. By contrast to other superwind models (e.g., Blöcker 1995), we find a *gradual* decline of $\dot{M}$ instead of an abrupt end of the superwind phase. It is caused by the rise of $T_{\rm eff}$ in the turn-off from the tip-AGB. This aspect should have consequences for the density profiles of CSE's and proto-PN's – i.e., density gradients of the inner, yet undisturbed, cool envelopes should be less steep.

4. Discussion

We consider this work as a first step to combine the so far separate worlds of stellar evolution models and detailed, self-consistent models of dust-driven winds to compute the final tip-AGB evolution and mass-loss history. In general, there is excellent agreement between our computations and a variety of observational facts, such as outer shell structure found in deep exposures of PN's in general, and detached circumstellar shells and envelopes in particular. To a significant extent, these results are, on a macroscopic scale, the direct consequence of the complex, temperature and density dependent micro-physics, dust-formation chemistry and radiative transfer – leading, in particular, to (1) a $T_{\rm eff}$ and mass-dependent (Eddington-like) critical luminosity L_c and (2) a mass-loss rate which is strongly $T_{\rm eff}$-sensitive.

Since the present version of our evolution code does not compute mixing associated with the dredge-up's, we cannot use the actual C:O surface ratio of our stellar models to define the mass-loss rate in a strictly self-consistent way. Fortunately, once a C-rich, dust-induced wind is established it is almost independent of the C:O ratio. Nevertheless, a critical point remains to be inspected: is

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a C:O ratio > 1 indeed reached *before* L reaches L_c? In fact, observational data support that assumption: for a tip-AGB stellar mass of 0.75 $M_\odot$ we obtain a minimum log L_c of about 3.6, that is $M_{bol} \approx -4.3$, while the bulk of carbon star M_{bol} values derived from HIPPARCOS parallaxes (Alksnis et al. 1998) already starts from about -3.7.

To conclude, we may say that despite the complexity of the problem, on both a macroscopic and a microscopic scale, and with the numerous different physical and chemical processes net-working together in a pulsating, C-rich and dust-induced superwind, we are able to compute quantitative models of the crucial final 10^5 years of stellar tip-AGB life, which are in excellent agreement with a variety of empirical facts and observational data.

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