Proceedings of 12th Cambridge Workshop on Cool Stars, Stellar Systems, & The Sun, 2003 University of Colorado.

An Improved Mass-loss Description for Dust-driven Superwinds

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Abstract. We consider the mass loss of stars during the final stages of their evolution. Our mass loss description for the tip-AGB is based on pulsating wind models in which the mass loss is driven by radiation pressure on dust grains, for a C-rich chemistry. From a grid of these models an improved approximative mass-loss rate formula has been derived which depends on the stellar parameters: effective temperature, luminosity, and mass only. The dependence of the mass-loss rate on the pulsation period has been taken into account by applying the observed period-luminosity relation for C-rich Miras. Since the wind models treat in detail the chemistry and micro-physics of the dust formation process, the resulting mass-loss rate depends strongly on the stellar effective temperature, reflecting the sensitivity of the dust formation process on the local thermodynamic conditions.

1. Introduction

Stellar evolution on the upper Asymptotic Giant Branch (AGB) is controlled by strong mass loss, since the time scales involved easily become shorter than the nuclear time scales, which dominate the stars' evolution during the earlier phases. In order to consistently include this strong mass loss in stellar evolution calculations with the final aim of deriving the amount of mass returned by these stars to the interstellar medium, the dependence of the tip-AGB mass loss on the actual stellar properties needs to be known. Here, we present a new mass-loss rate formula derived from consistent hydrodynamical wind models which include a detailed description of the dust formation process.

2. Wind Models for Long Period Variables (LPVs)

The formula presented here is based on a set of self-consistent, dynamical wind models for dust-forming carbon rich atmospheres. The calculation of these models (for details see Winters et al. 2000) include

- ⋆ time-dependent hydrodynamics

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- ⋆ (stationary, grey) radiative transfer
- ⋆ (equilibrium) chemistry
- ⋆ carbon grain formation, growth and evaporation processes

The pulsation of the star is simulated by a sinusoidally varying inner boundary characterised by a pulsation period P and a velocity amplitude Δu. Additional input parameters are just the stellar parameters: stellar mass M, effective temperature $T_{\rm eff}$, luminosity L, and the element composition, here in particular the abundance ratio $\epsilon_{\rm C}/\epsilon_{\rm O}$ of carbon over oxygen. For the carbon-rich case ($\epsilon_{\rm C}/\epsilon_{\rm O} > 1$) which we consider here, this ratio determines the amount of carbon available for dust formation, assuming that all the oxygen and an equal amount of carbon is locked up in CO molecules.

From these wind models a time averaged mass-loss rate can be derived which depends only on the above mentioned 6 input parameters.

3. Selection of the Models

For including mass loss in our stellar evolution calculations one needs a description which depends only on the parameters M, $T_{\rm eff}$ and L, i.e. we have to consider how to treat the dependence of $\dot{M}$ on the 3 remaining parameters.

We only selected wind models with sufficient radiative acceleration to maintain stable, dust driven winds which yield a high mass-loss rate typical for the tip of the AGB. In this case, the remaining parameters have been dealt with as follows:

- ⋆ **carbon-to-oxygen ratio $\epsilon_{\rm C}/\epsilon_{\rm O}$**
  The models with strong mass loss considered here show that the dependence of $\dot{M}$ on this input parameter can in fact be neglected (see also Arndt et al. 1997).
- ⋆ **piston amplitude Δu**
  Since $\Delta u \approx 5\,{\rm km\,s^{-1}}$ seems to be the best value for matching observed Mira light curves in the infrared, we based our mass loss description only on models with that piston amplitude.
- ⋆ **pulsation period P**
  For carbon-rich Miras there is an observed relation between period and luminosity: $\log P \propto 0.965 \cdot \log L$ (Groenewegen & Whitelock 1996). Our wind models cover the corresponding range of periods, and the period dependence of the mass loss can simply be merged with the luminosity term.

The selected set of models finally covers the parameter range of

M	$[M_\odot]$	0.8	–	1.2
T	[K]	2200	–	3000
L	$[L_\odot]$	3500	–	15000
P	[d]	104	–	1000

4. The Mass Loss Formula

To obtain the best representation of the theoretical mass-loss rates we applied a multidimensional maximum-likelihood method (Arndt et al. 1997). The derived formula $\log \dot{M}_{\rm fit} = -4.52 - 6.81 \cdot \log(T_{\rm eff}[K]/2600) + 1.54 \cdot \log(L[L_\odot]/10^4) - 1.95 \cdot \log M[M_\odot] + 0.959 \cdot \log(P[d]/650)$ has a correlation coefficient of 0.96 with the actual model mass-loss, and the mean relative error for $\log \dot{M}_{\rm fit}$ is ± 1.73 % . Together with the observed period-luminosity relation this yields

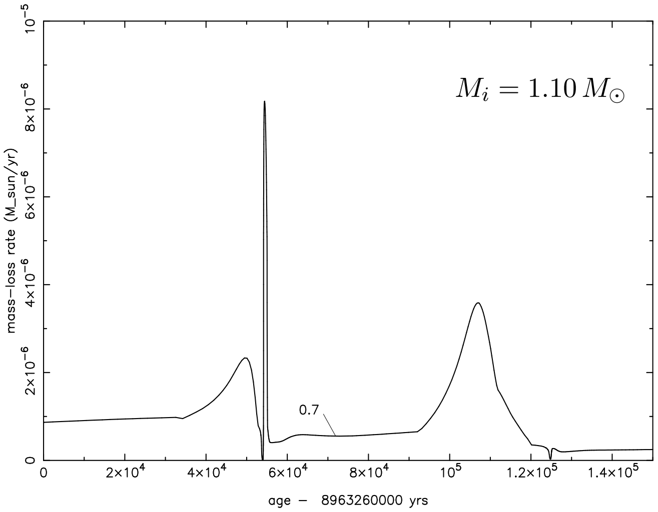
$$\log \dot{M}_{\rm fit} = 8.86 - 6.81 \cdot \log T_{\rm eff}/K + 2.47 \cdot \log L/L_\odot - 1.95 \cdot \log M/M_\odot$$

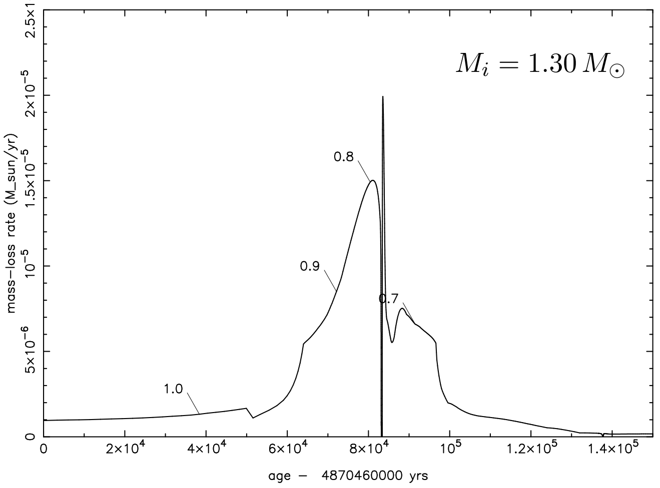
where $\dot{M}_{\rm fit}$ is given in units of $M_\odot {\rm yr}^{-1}$.

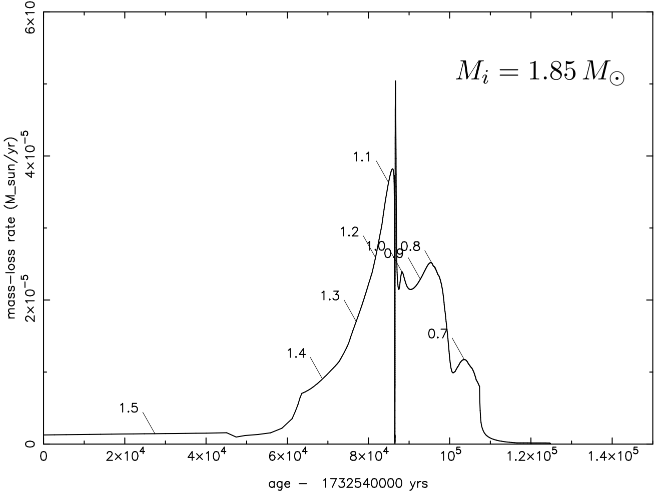
5. Results

5.1. Applying the mass loss description to tip AGB evolution

The following 4 graphs (Figs. 1 – 4) show the mass-loss rate history of stars with different initial masses when applying the above mass loss formula to stellar evolution computations on the tip-AGB (see also Schröder et al. 1999).




$M_i = 1.30\,M_\odot$
mass-loss rate (M_sun/yr)
age - 4870460000 yrs
0
5×10^-6
10^-5
1.5×10^-5
2×10^-5
2.5×10^-5
0
2×10^4
4×10^4
6×10^4
8×10^4
10^5
1.2×10^5
1.4×10^5
1.0
0.9
0.8
0.7


$M_i = 1.85\,M_\odot$
mass-loss rate (M_sun/yr)
age - 1732540000 yrs
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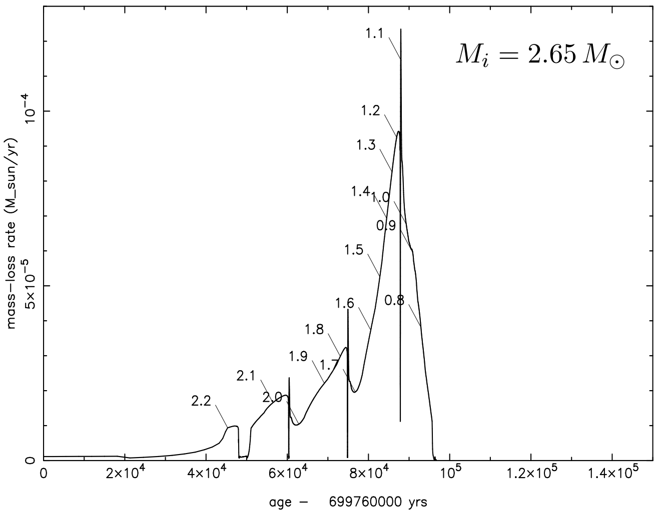
2×10^-5
4×10^-5
6×10^-5
0
2×10^4
4×10^4
6×10^4
8×10^4
10^5
1.2×10^5
1.4×10^5
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7


$M_i = 2.65\,M_\odot$
mass-loss rate (M_sun/yr)
age - 699760000 yrs
0
5×10^-5
10^-4
0
2×10^4
4×10^4
6×10^4
8×10^4
10^5
1.2×10^5
1.4×10^5
1.1
1.2
1.3
1.4
1.0
0.9
1.5
1.6
0.8
1.8
1.9
1.7
2.1
2.0
2.2

Note that:

- ⋆ Stars with initial masses M_i around 1.1 $M_\odot$ in general reach mass loss rates of only a few $10^{-6}\,M_\odot\mathrm{yr}^{-1}$ but can show strong bursts of superwind.
- ⋆ A strong superwind phase (i.e. $\dot{M} > 10^{-5}\,M_\odot\mathrm{yr}^{-1}$ in the final 30 000 years) is seen for initial masses $M_i \gtrsim 1.3\,M_\odot$. The peak mass loss increases with M_i and reaches $\dot{M} \approx 10^{-4}\,M_\odot\mathrm{yr}^{-1}$ at $M_i = 2.5\ M_\odot$.

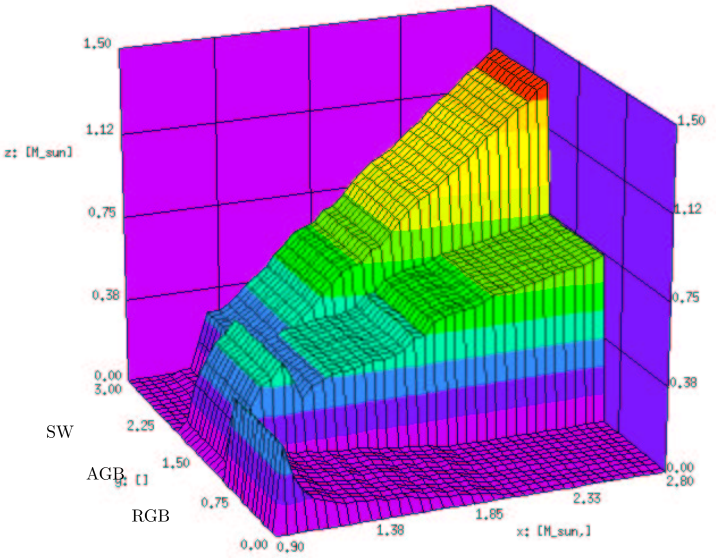
5.2. Total masses lost

The table below gives, for each initial mass, the mass lost in different evolution phases and the computed final stellar mass M_f - all in units of $M_\odot$. The AGB mass loss excludes mass lost during the superwind phase (SW), which means the final 30 000 years before the star leaves the AGB.

M_i	$\int \dot{M}_{RGB}$	$\int \dot{M}_{AGB}$	$\int \dot{M}_{SW}$	M_f	
1.00	0.24	0.20	—	0.55	
1.10	0.12	0.38	0.01	0.56	^{1})
1.20	0.09	0.47	0.03	0.58	^{1})
1.30	0.08	0.30	0.28	0.60	
1.40	0.07	0.37	0.31	0.61	
1.50	0.06	0.39	0.38	0.62	
1.60	0.05	0.41	0.46	0.63	^{2})
1.70	0.04	0.42	0.55	0.63	
1.80	0.03	0.45	0.62	0.64	
1.90	0.02	0.50	0.68	0.65	^{3})
2.05	0.001	0.58	0.79	0.66	
2.15	—	0.59	0.87	0.67	
2.25	—	0.63	0.92	0.68	
2.35	—	0.64	1.00	0.69	
2.50	—	0.67	1.11	0.70	

^{1}) only brief superwind burst(s)
^{2}) onset of core overshooting on MS at $M_i \approx 1.6 M_\odot$
^{3}) RGB evolution ends with He flash for $M_i \leq 1.95 M_\odot$

These values are displayed in Fig. 5. The x-axis gives the initial mass, the y-axis the 3 phases - RGB, AGB and Superwind (from front to back) and the z-axis the integrated mass loss in each phase.



Note that stars with about one solar mass lose a significant amount of matter on the RGB. Once the dust-driven, carbon-rich superwind sets in ($M_i > 1.3\,M_\odot$), stars lose about half of their mass during those final 30 000 years.

6. Conclusions

We have derived a simple formula for dust-driven, carbon-rich mass loss from detailed, self-consistent wind models, yielding the mass loss rate in terms of the stellar parameters. Applied to evolution models, this mass-loss description consistently yields both the evolution of tip-AGB superwinds and the total mass lost in that phase.

References

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