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Mass loss of dust-driven winds at subsolar metallicity

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Abstract. Intermediate mass stars contribute to the enrichment of the interstellar medium via mass-loss of the order of up to several $10^{-5}\,M_{\rm sun}\,{\rm yr}^{-1}$ during their evolution along the Asymptotic Giant Branch. As driving mechanism radiation pressure on dust grains formed in the cool atmospheres of these stars plays an important role. The stellar pulsation results in a levitation of the atmosphere, pushing the atmospheric gas into the dust formation window, a thermodynamic regime where density and temperature are favourable for grain formation. Radiation pressure then accelerates the dust particles and the surrounding gas is dragged along via frictional coupling, generating those massive outflows.

In our work, we are interested in the total mass lost by stellar samples with subsolar metallicities. In order to give a quantitative account, a description of the mass loss is needed which can be applied to stellar evolution calculations. Following the approach for solar metallicity stars we derive the mass-loss description from hydrodynamical wind models for long-period variables. The models have been adapted to the lower opacity, which is to be expected because of the low metallicity. This modification involves a proper description of the transport of radiation through a medium of arbitrary optical thickness.

In this contribution we present results obtained from models calculated with abundances as found in the Large Magellanic Cloud. The mass-loss history of single stars is examined as well as their integrated mass loss.

Key words. Stars: atmospheres – Stars: evolution – Stars: LMC

1. Introduction

In the last decade dynamical wind models have been developed which include the dust formation and growth processes (e.g., Fleischer et al. (1992)). The stellar pulsation enters as an inner boundary condition parameterised by period P and velocity amplitude $\Delta v_{\rm P}$. In addition to the stellar mass $M_\star$, effective temperature $T_\star$, and luminosity $L_\star$ the photospheric element abundances $\epsilon_{\rm i}$, notably the abundance ratio of carbon to oxygen, needs to be prescribed to characterise the amount of condensible material available for dust formation. For otherwise solar abundances, these models yield time averaged mass loss rates of up to a few 10^{-5} $M_\odot$ yr^{-1}, both for oxygen-rich and carbon-rich mixtures. This is consistent with rates inferred from, e.g. CO rotational line observations of asymptotic giant branch stars in the solar neighbourhood. In this contribution we focus on models with element abundances observed in the Large Magellanic Cloud (LMC).

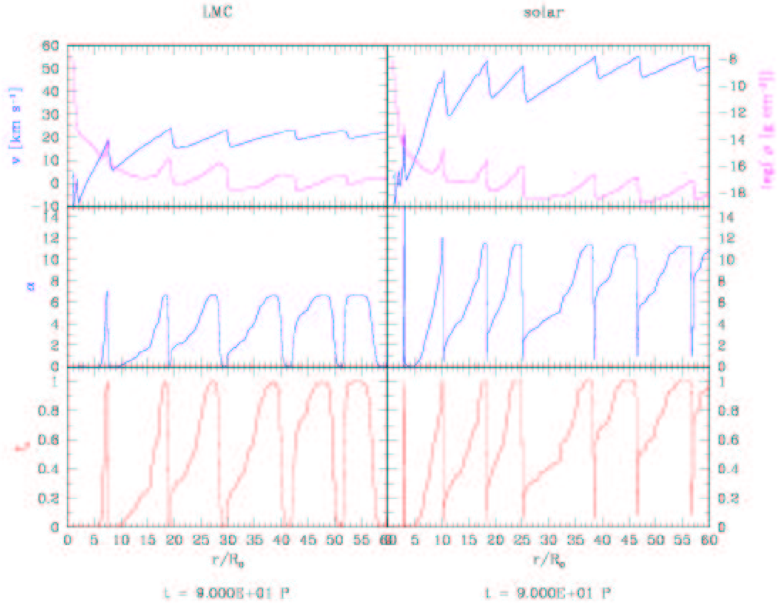

Fig. 1. Radial Structure of models with input parameters $L_\star = 10^4 L_\odot$, $T_\star = 2600$ K, $M = 1.0 M_\odot$, $P = 650$ d, $\Delta v_P = 2$ km s^{-1}, $\epsilon_C/\epsilon_O = 1.8$. Shown are (top to bottom) the outflow velocity v, the density ρ, the ratio of radiative to gravitational acceleration α, and the degree of condensation f_c.

2. Dynamical Wind Models

The following paragraphs contain a short summary of the wind models we use to acquire averaged mass loss rates. For a detailed description of the physical assumptions made in these models see Winters et al. (2000) and references therein. The models are started with a dust-free atmosphere where a carbon-rich mixture is considered for which chemical equilibrium is assumed in the gas phase. Considered are the concentrations of species relevant for carbon grain formation (H, H_2, C, C_2, C_2H and C_2H_2). Oxygen is assumed to be completely blocked in the CO molecule. The formation, growth, and evaporation of carbon grains is calculated according to the moment method by Gail & Sedlmayr (1988) and Gauger et al. (1990). The radiative transfer problem is solved using the Unno–Kondo method in the grey approximation (for details see Winters et al. (1997) and references therein) giving the radiative equilibrium temperature.

For less than solar metallicity the approximate treatment of the radiative transfer in the circumstellar shell is reconsidered. In the solar case the shell has been considered to be optically thick so that the flux-averaged dust extinction is determined by the local equilibrium radiation field. However, if the atmosphere is considered to be partly transparent, the dust grains are to some extent exposed to the direct radiation from the stellar photosphere. Therefore, the flux-mean dust opacity is for lower metallicity represented by assuming a non-local radiation field, which is interpolated in optical depth between the local equilibrium radiation and the stellar (black-body) radiation field.

3. Results And Discussion

3.1. LMC and solar models

Adopting LMC element abundances a multitude of models has been calculated with the updated code covering the parameter range:

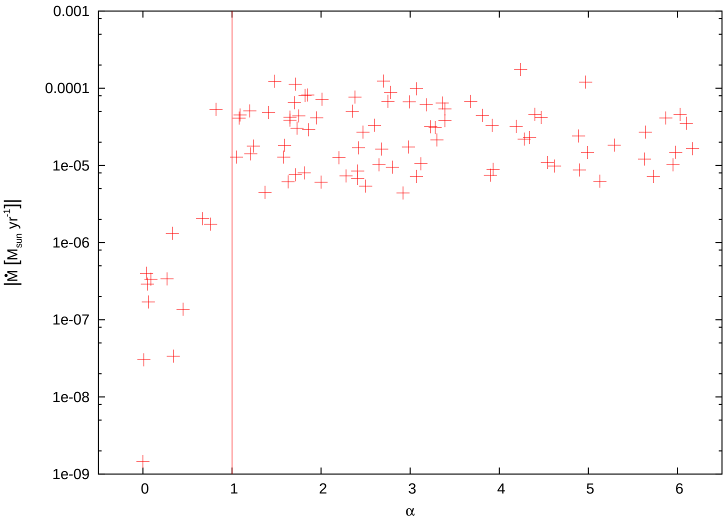

Fig. 2. Averaged mass loss rate over averaged ratio of radiative to gravitational acceleration for LMC models.

$L_\star$ [$L_\odot$]	5000 . . . 15000
$T_\star$ [K]	2200 . . . 3200
$M_\star$ [$M_\odot$]	0.7 . . . 1.0
$\epsilon_{\rm C}/\epsilon_{\rm O}$	1.3 , 1.8
P [d]	325 . . . 650
$\Delta v_{\rm P}$ [km/s]	2 , 5

Figure 1 shows the radial structure of two models calculated with the same input parameters but different element composition. The diagram illustrates the typical situation that the ratio of raditative to gravitational acceleration α and the outflow velocity are smaller in the LMC case. By averaging over time and radius several quantities have been computed which characterise the outflow of a model: the mass loss rate $\dot{M}$, the final outflow velocity v_∞, and the dust-to-gas ratio $\rho_{\rm d}/\rho_{\rm g}$. In the LMC case the final outflow velocity and the dust-to-gas raio are smaller, typically a factor of 0.5 and 0.5. . .0.8, respectively. Concerning the mass loss rate though, there is no trend to be noted being for some models even larger in the LMC case.

3.2. Resulting mass loss

Figure 2 shows for all models (with LMC abundances) the averages of mass loss rate over ratio of radiative to gravitational acceleration. Models with $\langle\alpha\rangle > 1$ exhibit a stable dust-driven wind (as for example in fig. 1), while the others show a quasi-static structure. For the derivation of a mass-loss formula therefore only models with $\langle\alpha\rangle > 1$ have been selected. Furthermore the velocity amplitude $\Delta v_{\rm P}$ has been fixed to 5 km s^{-1} (Wachter et al. 2002) and the abundance ratio $\epsilon_{\rm C}/\epsilon_{\rm O}$ to 1.8 (test calculations showed that the value of the mass loss rate does not change noticeably as long as a ”critical” value is exceeded).

Performing a multilinear least square fit of the form $\log\dot{M} = a_0 + a_1 * \log x_1 + \ldots$ the following formula results:

$$|\dot{M}[M_\odot\,{\rm yr}^{-1}]| = 3.80\times10^{-5}\times(M_\star[M_\odot])^{-2.56}\times\left(\frac{T_\star[{\rm K}]}{2600}\right)^{-7.44}\times\left(\frac{L_\star[L_\odot]}{10^4}\right)^{2.86}$$

with a correlation coefficient of $K = 0.98$.

3.3. Application to Stellar Evolution

For calculating stellar mass-loss histories resulting with this formula we use the stellar evolution code by P.P. Eggleton as summarised by

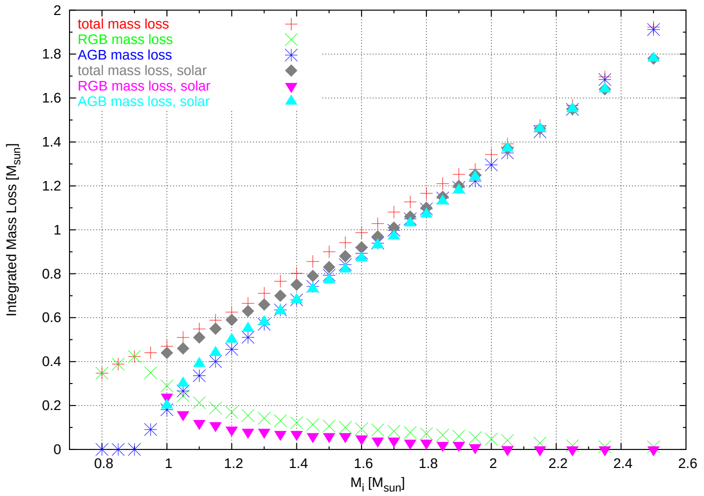

Fig. 3. Total mass lost over initial mass

Pols et al. (1995). There the mass loss is easily applied as a boundary condition. The condition $\langle\alpha\rangle > 1$ can be expressed in terms of a critical luminosity $L_{\rm crit}$, i.e. the above given formula is only valid when the stellar luminosity exceeds $L_{\rm crit}$. Before the star reaches $L_{\rm crit}$ on the tip of the AGB, we apply a modified Reimers law as presented by Schröder & Cuntz (2005). Evolutionary tracks with different initial masses have been computed for LMC-like element abundances. Figure 3 shows the resulting time-integrated mass loss for the grid of tracks (crosses). Additionally to the total mass lost, the fractions lost on the RGB and the AGB are plotted, respectively. For comparison earlier results for solar element abundances are shown as well (filled symbols). It can be seen that the total amount of mass lost is not lower for LMC-like abundances.

4. Conclusions

Comparing hydrodynamical wind models with element abundances as found in the LMC to corresponding solar models we find smaller final outflow velocities, and smaller dust-to-gas ratios, but no trend for the mass loss rates. The derived mass loss formula for LMC abundances shows as in the solar case the strongest dependence on the temperature reflecting the sensitivity of the dust complex to temperature. Applying the resulting formula to stellar evolution we find that basically same amounts of mass are lost by LMC and solar models.

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