A Massive Star Odyssey, from Main Sequence to Supernova
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The winds of Luminous Blue Variables and the mass of AG Carinae

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Abstract. We present radiation-driven wind models for Luminous Blue Variables and predictions of their mass-loss rates. A comparison between our theoretical results and observations of AG Car shows that the variable mass loss behaviour of LBVs is due the recombination/ionisation of Fe IV/III and Fe III/II. A present-day mass of 35 $M_\odot$ for AG Car is derived.

1. Introduction

Luminous Blue Variable (LBVs) are massive stars in a brief ($\sim 10^5$ yr) but violent post-main-sequence phase of evolution, during which they show a complex pattern of visual brightness and mass-loss variations. They are characterised by their visual light fluctuations of $\Delta V \simeq 1$ - 2 mag on timescales of years. These variations are referred to as 'S Doradus-type outbursts', and reflect an increasing/decreasing effective temperature of the star at approximately constant luminosity. The associated mass-loss changes are complex. In some cases, the mass loss increases while the star cools (*e.g.*, R 71), whereas in other cases (*e.g.*, R 110) the behaviour is the exact opposite: as the star cools, its mass-loss rate drops. Radiation-driven wind models of OBA supergiants (Vink *et al.* 2000) show, that stars change their wind characteristics as a function of $T_{\rm eff}$, most notably at spectral types B1 and A0, where for decreasing temperature, $\dot{M}$ jumps upwards by factors of five. This is due to changes in the ionisation balance of iron, which affects the line force. Here, we investigate whether these 'bi-stability jumps' can also explain the $\dot{M}(T_{\rm eff})$ behaviour of LBVs.

2. The mass loss behaviour of LBVs: the case of AG Car

Typical results for the $T_{\rm eff}$ behaviour of LBVs are shown in Figure 1a for three different ratios of the terminal velocity to the escape velocity ($v_\infty/v_{\rm esc}$). It shows that there are ranges in $T_{\rm eff}$ where $\dot{M}$ is predicted to increase, and others where $\dot{M}$ is expected to decrease. The trend towards a lower mass loss is due to a growing mismatch between the position of the bulk of the driving lines (mostly in the UV) and the location of the flux maximum, which shifts towards the optical for cooler stars. The increases in $\dot{M}$ are due to recombinations of Fe IV to Fe III at about 21 000 K, and of Fe III to Fe II at $\sim$10 000 K. Ultraviolet

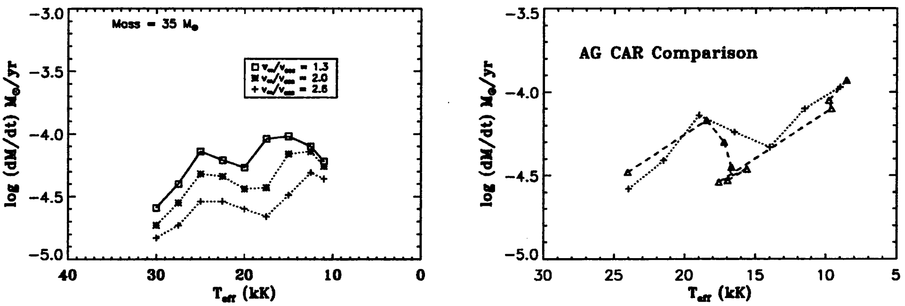

Figure 1. Predicted mass-loss rates for an LBV of 35 M$_\odot$, and $L = 10^6$ L$_\odot$. *Left (a):* $\dot{M}$ behaviour for different ratios of $(v_\infty/v_{\rm esc})$. *Right panel (b):* comparison of predicted (dotted line) and observed (dashed line) mass-loss rates for AG Car.

observations have shown that these 'bi-stability' jumps occur at spectral types B1 and A0, respectively (Lamers *et al.* 1995).

Figure 1b shows a comparison between our models and observed mass-loss rates of AG Car, using Hα as a diagnostic (Stahl *et al.* 2001). The observed and theoretical mass-loss rates agree to within 0.1 dex, which is a surprisingly good result considering that the $\dot{M}$ fluctuations of up to 0.5 dex show a complex behaviour. Note that we have applied a corrective shift of $\Delta T_{\rm eff} = -6000$ K to our predictions, to account for a systematic inaccuracy in our calculations of the ionisation balance of iron. The applied shift, however, is consistent with the one needed to match the bi-stability jumps observed in normal BA supergiants.

We conclude that the winds of LBVs are driven by radiation pressure on spectral lines and that the mass-loss variability is due to changes in the ionisation balance of iron.

3. The mass of AG Car

The mass-loss rates are also sensitive to stellar mass: $\dot{M} \propto M^{-1.8}$ (Vink & de Koter 2002). This allows one to constrain LBV masses, which is difficult for more conventional methods. Comparing the AG Car data with our $\dot{M}(T_{\rm eff})$ predictions for different masses yields a best fit to the present day mass of 35 ± 5 M$_\odot$. Note that Stahl *et al.* (2001) did not account for possible clumping of the wind of AG Car. If clumping plays a role, this would imply that the $\dot{M}$ values derived from Hα are too high. Consequently, our mass derivation would be underestimated.

References

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