A Massive Star Odyssey, from Main Sequence to Supernova
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Hydrodynamic model atmospheres for hot stars

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Abstract. Recent non-LTE models for expanding atmospheres, accounting for iron group line-blanketing and clumping, show a radiative acceleration which supplies a large part of the driving force of WR and O star winds. Aiming at the calculation of fully consistent wind models, we developed a method to include the solution of the hydrodynamic equations into our atmosphere code, taking into account the radiation pressure from the CMF radiation transport. In the present work we discuss the resulting wind acceleration for "standard" WR and O star model atmospheres, and present a hydrodynamically consistent non-LTE model for the O star ζ Pup. In addition we demonstrate the effect of clumping on the radiative acceleration.

1. Introduction

Our present atmosphere models consider model atoms of H, He, C, N, O, Si, and the iron group, which include several millions of line transitions (Gräfener, Koesterke, & Hamann 2002; Koesterke, Hamann, & Gräfener 2002). The radiation transport is calculated in the comoving frame on a fine frequency grid ($\approx 10^5$ frequency points) which covers the whole relevant frequency range and resolves all line transitions.

This detailed treatment of the radiation field offers the opportunity to calculate the radiative acceleration directly in the CMF radiation transport

$$a_{\rm rad} = \frac{1}{\rho}\frac{4\pi}{c}\int_0^\infty \kappa_\nu H_\nu \, \mathrm{d}\nu.$$

As this calculation is performed without any approximations, all important effects like multiple line scattering, line blocking, or the "finite disk correction" are automatically included. Furthermore, the transition from the optically thick photosphere to the stellar wind is accounted for in a realistic way.

2. Standard models

In the first part of Fig. 1 we present the radiative acceleration of two standard atmosphere models with prescribed (β-type) velocity law and mass loss rate. For the early-type WC star WR 111 (with a wind efficiency of $\eta = \dot{M} v_\infty/(L_\star/c) = 4.8$) the acceleration of the outer part of the wind is easily explained by radiation pressure. Nevertheless both models show deficits in the radiative force, especially in the acceleration region directly above the photosphere. For ζ Pup 30% and for WR 111 40% of the wind power $L_{\rm wind} = \dot{M}(v_\infty^2/2 + M_\star G/R_\star)$ are provided by the radiation force.

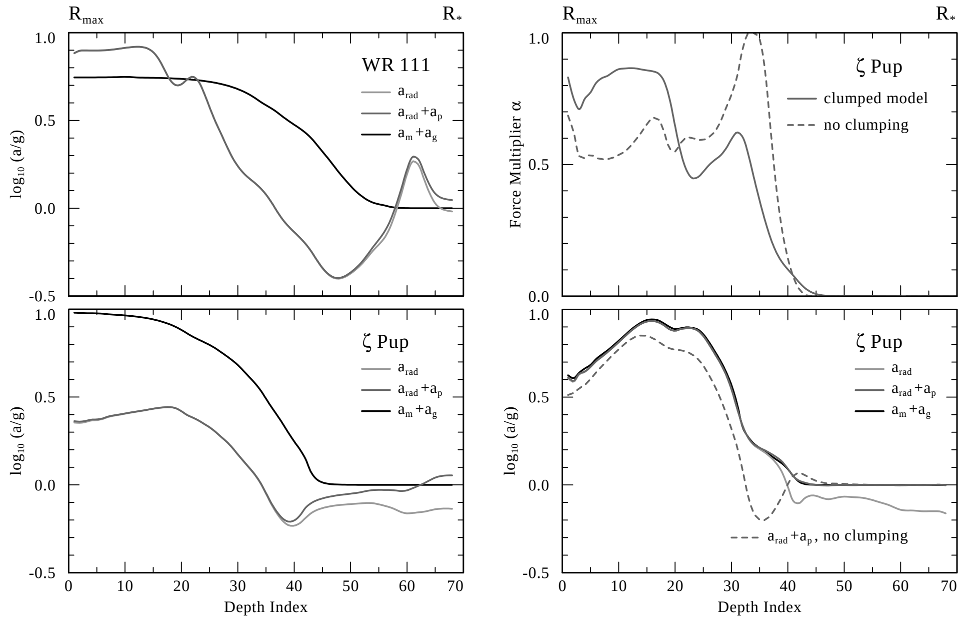

Figure 1. The wind acceleration in units of the local gravity $g(r)$ vs. depth index (outer boundary: 1; inner boundary: 70). Left panels: Standard atmosphere models for ζ Pup and WR 111. The mechanical + gravitational acceleration as implied by the adopted β-law (black) compared to the wind acceleration calculated from the radiation + gas pressure in the atmosphere models (grey). Right panels: Hydrodynamic model for ζ Pup. Bottom: The wind acceleration consistently fits the mechanical + gravitational acceleration of the hydrodynamic wind structure. The broken lines indicate the effect of switching off clumping. Top: The "effective" force multiplier α as determined in our calculations by variation of the velocity structure $v(r)$.

3. Hydrodynamic models

In the right panels of Fig. 1 we present a model for ζ Pup ($L_\star = 10^{5.8} L_\odot$, $T_\star =$ 37 kK) with a hydrodynamically consistent atmosphere structure. When the stellar mass is adjusted to $M_\star = 48\,M_\odot$, the model ($v_\infty = 2100\,\mathrm{km/s}$, $\dot{M} = 10^{-6.3} M_\odot/\mathrm{yr}$) reproduces the observed terminal wind velocity but *not* the mass loss rate of ζ Pup (possibly due to still lacking trace elements like P, S, Ne or Ca).

The model is calculated with a very high clumping factor, which increases up to a value of $D = 64$ in the outer part of the wind. The effect of switching D back to 1 is indicated by the broken lines in Fig. 1. Especially in the region directly above the photosphere the radiative acceleration is considerably enhanced by assuming a clumped wind structure.

References

Gräfener, G., Koesterke, L., & Hamann, W.-R. 2002, A&A, 387, 244

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