Massive Stars in Interacting Binaries
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Hydrodynamic model atmospheres for WR stars: first results and their consequences for interacting winds in massive binary systems

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Abstract. We present the first models for the expanding atmospheres of WR stars that combine a full non-LTE radiative transfer with a self-consistent hydrodynamic solution for the wind structure. By the inclusion of the Fe M-shell ions (the so-called 'Hot Iron Bump' opacities) in our models, the radiative driving in deep atmospheric layers is considerably increased. For the case of an early-type WC star we find that the WR wind is initiated by the radiative driving on these opacities, at large optical depth. The acceleration of the outer part of the wind is performed by iron-group ions of lower excitation in combination with C and O. Consequently, the wind structure shows two acceleration regions. One close to the hydrostatic wind base in the optically thick part of the atmosphere, and one farther out in the wind. In addition, our calculations provide important parameters for the modeling of interacting winds in massive binary systems. In particular, the force multiplier parameters as determined within our models, are qualitatively different from the values derived for O-star winds.

1. WR wind models

In their recent work, Nugis & Lamers (2002) addressed the question whether it's possible to drive WR-type winds by the radiation pressure on line opacities in deep atmospheric layers. By means of a critical-point analysis based on OPAL Rosseland mean opacities, they found that for the initiation of WNE & WC star winds the sonic point must be located *below* the 'Hot Fe-bump' opacity peak, at temperatures above 160 kK, and correspondingly large optical depths around $\tau_s \approx 20$.

In the present work, we include the Fe-bump opacities, i.e., Fe-ions up to Fe XVII, into our non-LTE models. By this detailed modeling, we overcome the limitations due to the use of Rosseland mean opacities in the work of Nugis & Lamers (2002). Moreover, our models provide a solution of the hydrodynamic equations, accounting for the radiative force as obtained from the radiation transport. On this way it is possible to model the *complete wind structure* in a self-consistent manner. A detailed description of our models can be found in Gräfener & Hamann (2005); Hamann & Gräfener (2003); Koesterke et al. (2002); Gräfener et al. (2002).

Concerning the temperature regime where the sonic point is located, our models are in line with the results of Nugis & Lamers (2002). However, considerably higher core temperatures are needed to allow for the acceleration of the wind material *above* the optically thick regime. For a WC star model with a core temperature of $T_\star = 140\,\mathrm{kK}$ we obtain a self-consistent solution with

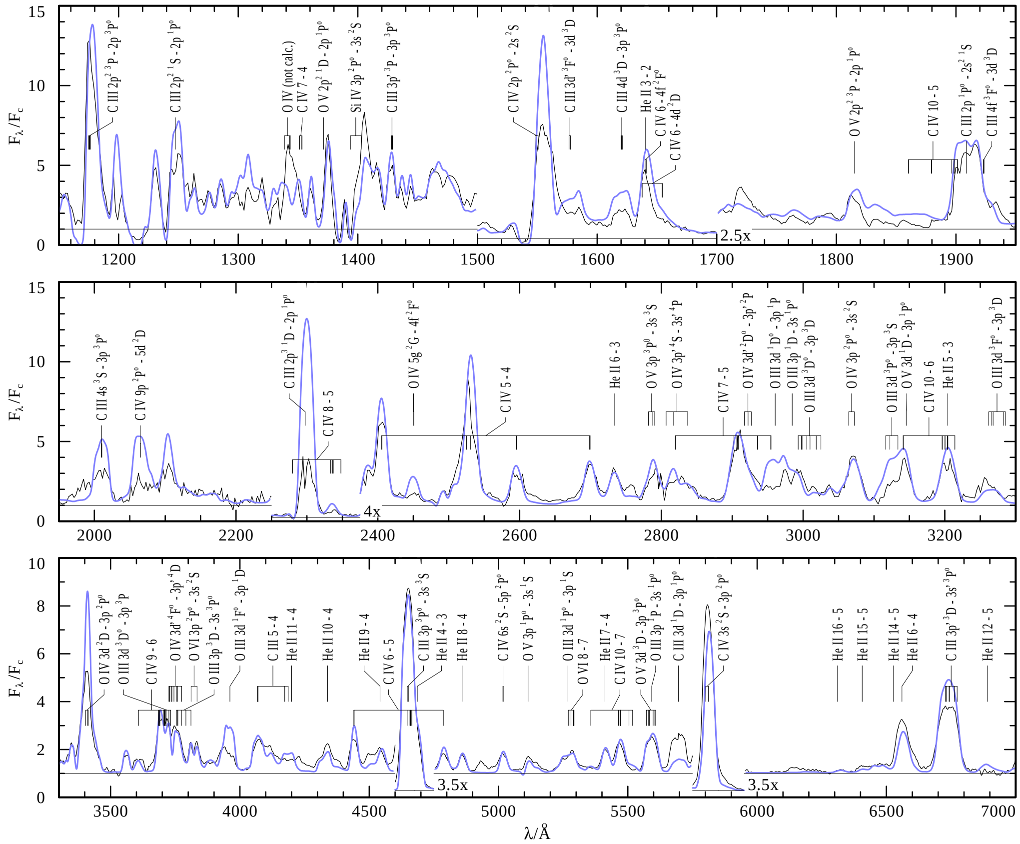

Figure 1. Comparison of the synthetic spectrum of our hydrodynamic model (thick line, grey) to the observed spectrum of WR 111 (thin line). Prominent spectral lines are identified. After correction for interstellar extinction, the observed flux and the model flux are both divided by the model continuum. Note that the model flux has been scaled down by 0.18 dex to match the absolute flux level of the observation.

$T_{\rm s} = 199\,$kK and $\tau_{\rm s} = 5.4$ at the sonic point (due to the higher $T_\star$, τ_s turns out much smaller).

The WC star model is calculated for a mass of $13.63\,M_\odot$ and a luminosity of $L_\star = 10^{5.45} L_\odot$. Surface abundances of $X_{He} = 0.33$, $X_{\rm C} = 0.6$, $X_{\rm O} = 0.06$, and solar metallicity are assumed. With a clumping factor of $D = 50$, we obtain a mass-loss rate of $\dot{M} = 10^{-5.14}\,M_\odot/{\rm yr}$ and a terminal wind velocity of $v_\infty = 2010\,{\rm km/s}$. In Fig. 1, the synthetic model spectrum is compared to the observed spectrum of WR 111 (WC 5). Although the fit quality would not be sufficient for a quantitative analysis of this specific object, the hydrodynamic model clearly displays the spectral characteristics of an early-type WC star.

The relatively high clumping factor of $D = 50$ has been chosen to compensate a lack of radiative acceleration in intermediate wind layers (around 1000 km/s), which is possibly due to the omission of trace elements like P, S, Ne, Ar, and Ca in our models. Nevertheless, high clumping factors around

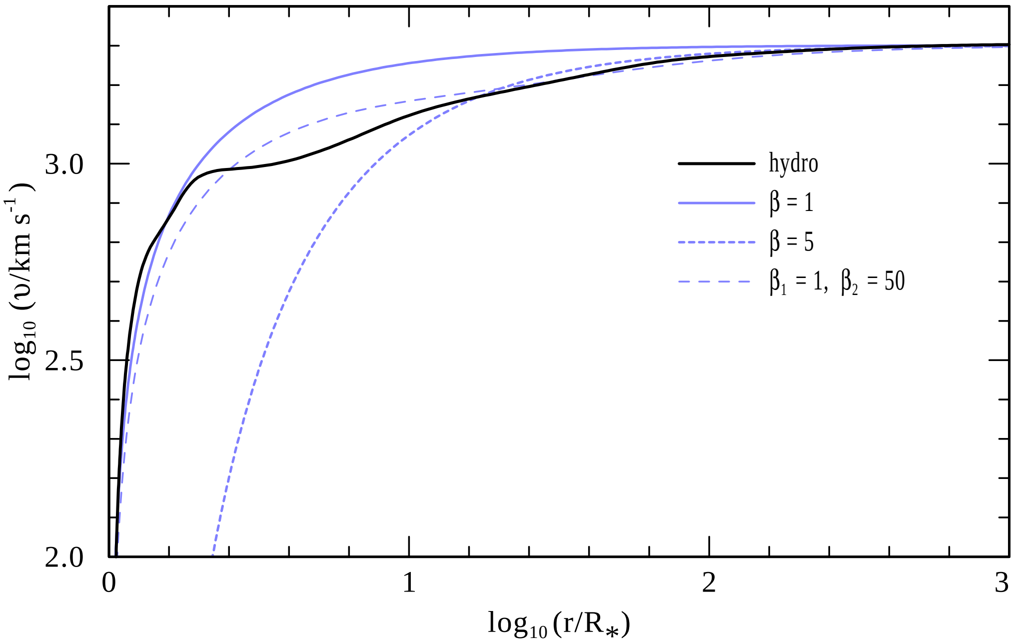

Figure 2. Velocity structure of the hydrodynamic model (black) compared to different β-type velocity laws and a double-β law as proposed by Hillier & Miller (1999).

$D = 10$ *are* observed for WC stars, and the influence of D, e.g. on the derived mass-loss rates in spectral analyses, only goes with $\sqrt{D}$.

In Fig. 2, the velocity structure of our hydrodynamic model is compared to β-type velocity laws with $\beta = 1$ and $\beta = 5$, and a double-β law as proposed by Hillier & Miller (1999) ($v_\infty = 2000\,\mathrm{km/s}$, $v_{\rm ext} = 400\,\mathrm{km/s}$, $\beta_1 = 1$, and $\beta_2 = 50$). Clearly, the strong acceleration in the inner part, which is due to the 'Hot Iron Bump' opacities, is best described by $\beta = 1$. The outer part, on the other hand, tends towards higher β, in accordance with the finding by Lépine & Moffat (1999) who deduced high values ($\beta > 3$) for the outer wind regions from variations in emission line-profiles.

2. The radiative acceleration

In Fig. 3, the radiative acceleration $a_{\rm rad}$ within our hydrodynamic model is compared to a model with the same parameters, but with a *prescribed* $\beta = 1$ velocity law. Although the velocity distributions $v(r)$ are completely different for both models, they show remarkably similar values of $a_{\rm rad}$. This already indicates a minor dependence of $a_{\rm rad}$ on the velocity gradient $v'(r)$.

For models of line-driven winds, this dependence is usually expressed by a parametrization of the form

$$a_{\rm rad} = a_{\rm Th}\, M(t) \equiv a_{\rm Th}\, k\, t^{-\alpha} \quad \text{with} \quad t = \sigma_e\, \rho\, v_{\rm th}/v',$$

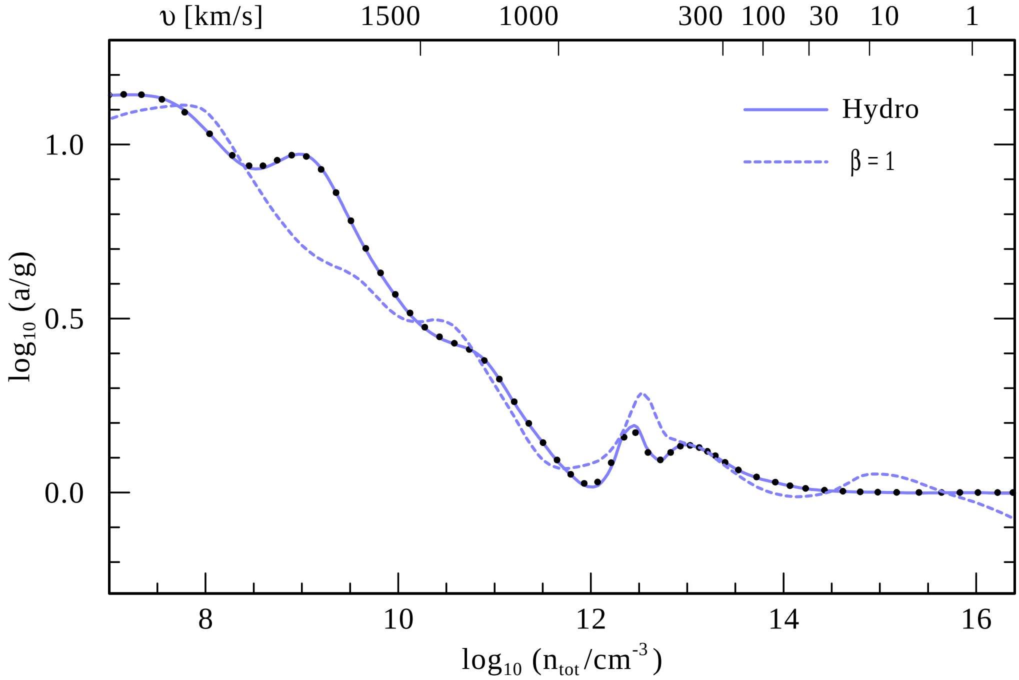

Figure 3. Wind acceleration in units of the local gravity for our hydrodynamic model, compared to a model with a *prescribed* $\beta = 1$ velocity law. The solid grey line indicates the acceleration $a_{\rm wind}$ due to radiation + gas pressure, as calculated within our models. $a_{\rm wind}$ is in precise agreement with the mechanical + gravitational acceleration ($a_{\rm mech} + a_{\rm grav}$, black dots) due to the hydrodynamic velocity structure and the stellar mass.

where the force multiplier M is expressed by the parameters k and α. Whereas k indicates the strength of the line force, α is a measure for the dependence of $a_{\rm rad}$ on v'.

In our models, α is determined by a global variation of the velocity field in the radiation transport. The resultant values are plotted in Fig. 4, together with an O star model from Gräfener & Hamann (2003). For the O star, values around 0.7 are obtained in the outer part of the wind, as expected from the standard theory for radiatively driven winds (Castor et al. 1975). For the WR model, on the other hand, values close to zero indicate a weak dependence of the radiative force on v'. Due to the complexity of the models, it is difficult to identify the reason for this behavior. An inspection of the detailed radiation field, however, indicates that the expected increase of $a_{\rm rad}$ for increasing v', is suppressed by the increasing number of line-overlaps for a larger velocity dispersion.

3. Radiative wind braking in WR+O binary systems

For the colliding winds in WR+O binary systems, the results from the previous section suggest that the efficiency of *radiative wind braking* may be affected by the low values obtained for the parameter α. Due to the high WR mass-loss rates, the ram balance in these systems is often completely dominated by the

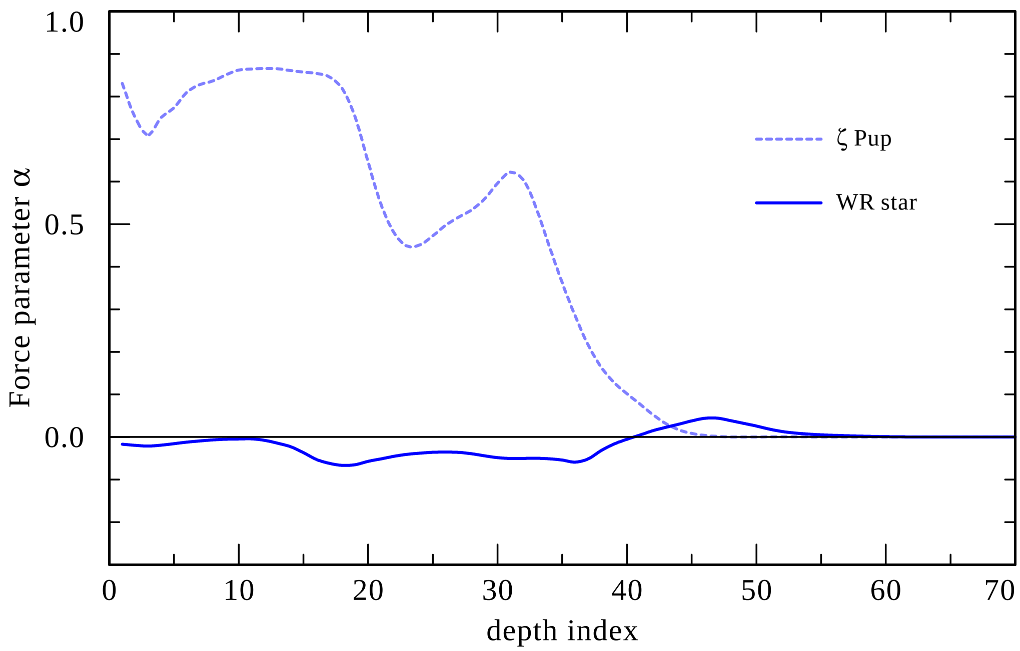

Figure 4. The force multiplier parameter α as calculated within our models *vs.* radial depth index (1: outer boundary, 70: inner boundary).

WR wind. Close to the O star, however, the radiative momentum L/c due to the O star, by far exceeds its wind momentum $\dot{M}v$. Close to the O star surface, the deceleration of the WR wind is therefore chiefly due to the radiation force. In their pioneering work, Gayley et al. (1997) gave an analytical description of this process, based on estimated values of $k = 0.15, 0.3, 0.8$ and $\alpha = 0.6$.

In the present work, we have modified the outer boundary condition of our WR atmosphere models to mimic the diluted radiation field of an O star binary partner, and thus, to determine the relevant force multiplier parameters on the connecting line between both stars. As example we choose the WC 8 + O 7.5 system γ^2 Velorum, which has an eccentric orbit with $d = 150$–$370\,R_\odot$. Adopting the stellar parameters by De Marco & Schmutz (1999); De Marco et al. (2000) ($L_{\rm WR} \approx L_{\rm O} = 2\,10^5 L_\odot$, WR star: $\dot{M} = 1.0\,10^{-5} M_\odot/\text{yr}$, $v_\infty = 1550\,\text{km/s}$ O star: $\dot{M} = 1.8\,10^{-7} M_\odot/\text{yr}$, $v_\infty = 2500\,\text{km/s}$), the braking radius R_b due to ram balance alone gives $R_b = 4.1\,R_{\rm O}$ for $d = 370\,R_\odot$, $R_b = 2.7\,R_{\rm O}$ for $d = 260\,R_\odot$, and $R_b < R_{\rm O}$ for $d = 150\,R_\odot$.

For our test calculations we take the WC model from the previous section, and set the outer boundary condition according to a black body with 35 kK at a distance of $260\,R_\odot$ (which corresponds to a location *within* the WR atmosphere model at a wind velocity of $\approx 0.97\,v_\infty$). In analogy to our previous results for single stars, we obtain values of $\alpha \approx 0$ for this configuration. However, as demonstrated in Fig.5, the force multiplier M, which is of the same order of magnitude as k for $\alpha \approx 0$, reaches values of 50–100 in the region close the O star surface (at 2–3 $R_{\rm O}$). Utilizing the formula given by Gayley et al. (1997), we thus obtain a braking radius of $R_b \approx 2.5\,R_{\rm O}$, indicating that radiative braking is still dominant

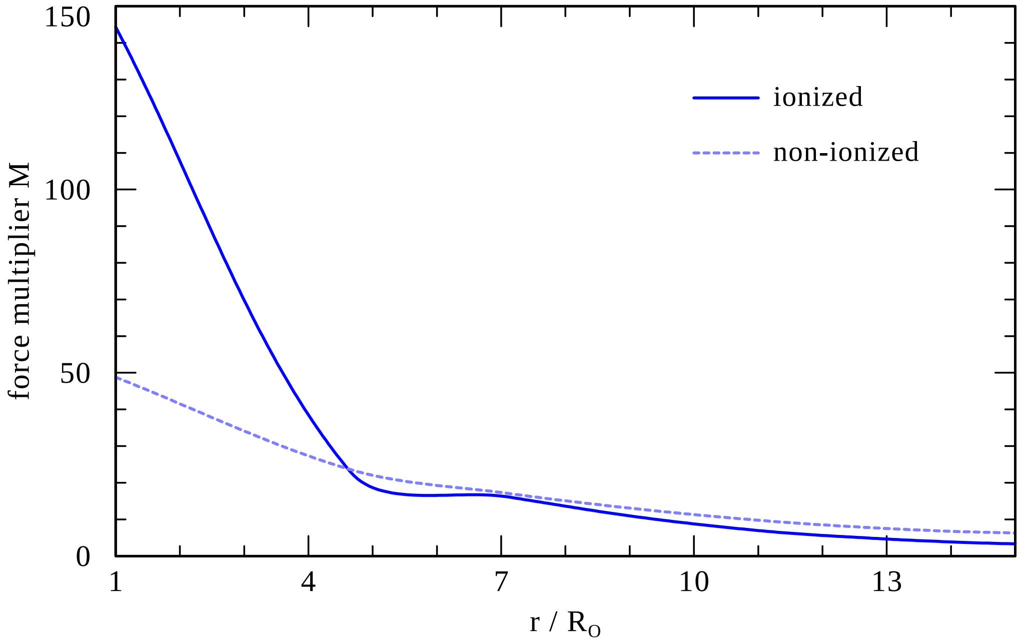

Figure 5. Force multiplier M for the O star radiation field *vs.* distance from the O star center in R_O. Due to the ionization of the WR wind material by the radiation of the O star, the force multiplier, and therefore the efficiency of radiative wind braking is considerably enhanced.

for small separations. Moreover, we compare in Fig. 5 an 'ionized' model, where the atomic populations are calculated consistently with the *combined* O + WR radiation field, to a 'non-ionized' model where the populations are taken directly from the single star model. The latter shows considerably smaller values of M, i.e., the braking efficiency is enhanced due to ionization effects.

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