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WR wind models: [WC]-type CSPN vs. massive stars

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Abstract. The optically thick stellar winds of Wolf-Rayet (WR) stars have recently been explained by means of hydrodynamic model atmospheres. In the present talk we discuss the physical processes that lead to their formation for the case of young massive stars as well as for [WC]-type CSPN. We explain why we expect WR-type mass loss only in specific temperature regimes, and discuss the possibility pulsational wind driving for other cases.

1. PoWR hydrodynamic model atmospheres

The Potsdam Wolf-Rayet (PoWR) hydrodynamic model atmospheres combine fully line-blanketed non-LTE atmosphere models with the equations of hydrodynamics (for details see Gräfener & Hamann 2005; Hamann & Gräfener 2003; Koesterke et al. 2002; Gräfener et al. 2002). The wind structure ($\rho(r)$ and $v(r)$) and the temperature structure $T(r)$ are computed in line with the full set of NLTE level populations, and the radiation field in the co-moving frame (CMF). In contrast to all previous approaches, the radiative wind acceleration $a_{\rm rad}$ is obtained by direct integration

$$a_{\rm rad} = \frac{1}{c} \int \chi_\nu F_\nu {\rm d}\nu, \tag{1}$$

instead of using of the Sobolev approximation. In this way complex processes like strong line overlap, or the redistribution of radiation, are automatically taken into account. Moreover, the models allow for small-scale wind clumping (see Hamann & Koesterke 1998). The models describe the conditions in WR atmospheres in a realistic manner, and provide synthetic spectra for a direct comparison with observations.

Utilizing these models, we recently obtained the first fully self-consistent Wolf-Rayet wind model for a Pop I WC star (Gräfener & Hamann 2005). Moreover, we have examined the mass loss from late-type WN stars and its dependence on metallicity (Gräfener & Hamann 2006, 2007).

2. WR wind dynamics

The wind momenta of WR stars lie typically above the single scattering limit ($\dot{M} v_\infty > L/c$). If WR winds are radiatively driven this means that photons must be absorbed and re-emitted several times before they escape the system. A direct consequence of this is that the flux-mean optical depth τ_W of the wind must be large. Photons originating from the hydrostatic layers are on average scattered τ_W^2 times in the wind. Because they perform a random walk these photons transfer a momentum of $\tau_W L/c$ per time interval to the wind. The resulting wind momentum is thus of the same order of magnitude, i.e., $\dot{M}v_\infty \approx \tau_W L/c$ (the wind momentum is actually slightly lower because a part of the radiative momentum is used to overcome the gravitational potential of the star). If a WR-type wind is radiatively driven its wind efficiency factor $\eta = \dot{M}v_\infty/(L/c)$ is thus of the same order as the wind optical depth τ_W. Note that in this context τ_W denotes the flux-mean optical depth of the sonic point (see, e.g., Sect. 7.2.2 in Lamers & Cassinelli 1999, for an exact derivation).

The large wind optical depth τ_W is also responsible for the spectral appearance of WR stars. For large τ_W the ionizing radiation from the static layers is absorbed within the wind. This leads to strong recombination and, via recombination cascades, to the observed WR emission line spectra. The fact that WR emission lines are observed in line with large efficiency factors η is thus a direct hint that τ_W is large for WR stars and WR-type winds are radiatively driven.

To generate large τ_W a large flux-mean opacity is needed directly above the sonic point, in combination with a large density scale height H_ρ. We thus expect WR-type mass loss to occur 1) close to the Eddington limit when H_ρ becomes large, and 2) in temperature regimes where the sonic point is located close to the Fe-opacity peaks (see also Nugis & Lamers 2002).

3. Results for Pop I WR stars

According to our wind models WR-type mass loss indeed occurs for high L/M ratios, when the Eddington factor Γ_e approaches unity. Also the sonic point temperatures in our models lie in the expected range (≈ 200 kK for early WC subtypes, corresponding to the hot Fe-peak; 30–45 kK for late WN subtypes, corresponding to the cool Fe-peak). Because of this our models predict two distinct regimes of effective core temperatures for WR stars. For early WC subtypes very high core temperatures of the order of $T_\star \approx 140$ kK are required (Gräfener & Hamann 2005). WNL subtypes can be reproduced successfully for cooler temperatures, in the range $T_\star = 30$–50 kK (Gräfener & Hamann 2006, 2007). For intermediate values of $T_\star$ our models do not provide enough radiative force in the deep atmospheric layers. Note that Glatzel et al. (this volume) have pointed out that WR-type mass loss might be supported by strange-mode pulsations in this regime.

The high L/M ratios which are mandatory for WR mass loss can be reached in different ways. He-burning stars have high L/M because of their large mean molecular weight. H-burning stars, on the other hand, can reach the WR state if their masses are extremely high. This is the case for the H-rich WNLh stars in young stellar clusters. Spectral analyses with hydrodynamic PoWR models imply very high masses, of the order of 80–100 $M_\odot$ for two objects in Carina OB 1 (Gräfener & Hamann 2006, 2007).

An important feature of WR-type winds is their dependence on the wind clumping factor $D(r)$ (see Hamann & Koesterke 1998). The wind acceleration roughly scales as $a_\mathrm{rad} \propto \sqrt{D}$. This effect is caused by the dominance of recombination processes in WR winds. An increase of D increases the mean $\langle\rho^2\rangle$, and

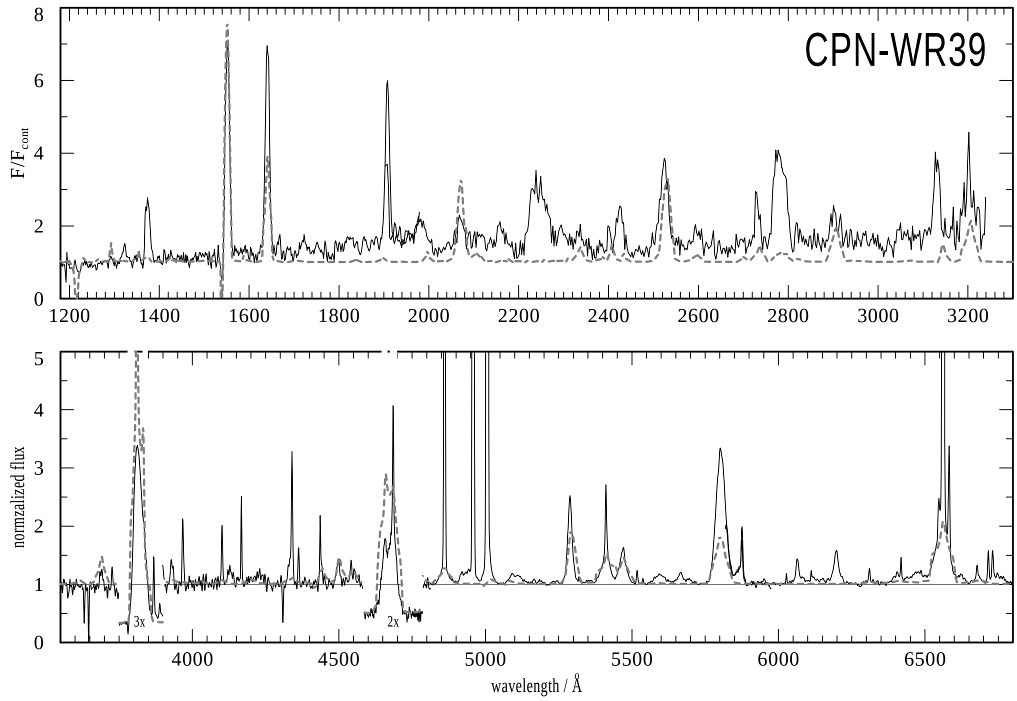

Figure 1. Tentative spectral fit of the [WC]-type CSPN CPN-WR 39 with a hydrodynamic PoWR atmosphere model. To reproduce O VI 3811 an extremely high core temperature is needed ($T_\star = 200\,\mathrm{kK}$). Other steallar parameters are: $M_\star = 0.6\,M_\odot$, $L_\star = 5000\,L_\odot$, $X_\mathrm{He} = 0.48$, $X_\mathrm{C} = 0.35$, $X_\mathrm{O} = 0.15$, $X_\mathrm{Fe} = 1.6\,10^{-3}$, $D = 100$. The wind parameters obtained from our model are: $\dot{M} = 10^{-7.5}\,M_\odot/\mathrm{yr}$, $v_\infty = 2120\,\mathrm{km/s}$.

thus mimics a denser wind with a larger mean opacity. For models of early-type WR stars we usually have to choose relatively large clumping factors around $D = 50$ to reproduce the observed terminal wind velocities. As observational estimates lie more around $D = 10$, our models might thus underestimate a_rad by roughly a factor of two. Note, however, that the observational estimates rely on the strength of the electron scattering wings of strong emission lines. This diagnostics is restricted to regions close to the stellar surface where the electron densities are large. A strong radial dependence of D thus might also resolve this discrepancy.

4. [WC]-type CSPN vs. massive stars

PN central stars have on average slightly lower L/M ratios than Pop I WR stars (L/M ≈ 3000–20000 in solar units, vs. 15000–30000 for Pop I WR stars). The more luminous central stars however reach similar L/M ratios as massive WR stars and could thus also form WR-type winds. For the same reason as for massive stars we expect the enhanced mass loss to occur in two distinct temperature regimes. For galactic [WC] central stars such a bimodal subtype distribution is indeed observed. Also the fact that the gap between hot [WCE/WO] stars and cool [WCL] stars is filled by the WELS which have much weaker winds (Gesicki et al. 2006, see also Marcolino et al. this volume) is in agreement with our expectations.

In Fig. 1 we present a tentative spectral fit of a hot [WC]-type central star with a self-consistent PoWR wind model. The model is computed for standard stellar parameters ($0.6\,M_\odot$, $5000\,L_\odot$). To reproduce the strong O VI feature at 3811 Å a very high core temperature of $T_\star = 200\,\mathrm{kK}$ is needed. Moreover, the observed terminal wind speed is only reproduced with a very large clumping factor ($D = 100$). This value is even larger than the value from our previous modelling of a Pop I WCE star ($D = 50$, Gräfener & Hamann 2005). Although in most cases the clumping factor for [WC]-type CSPN cannot be determined from observations a value of 100 seems to be quite large. This could be a hint on an additional contribution of exotic elements, like the products of the s-process, to the wind driving of CSPN.

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