A Massive Star Odyssey, from Main Sequence to Supernova
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Wolf-Rayet star parameters from spectral analyses

Wolf-Rainer Hamann[1], Götz Gräfener[1], and Lars Koesterke[2]

[1]*Lehrstuhl Astrophysik, Institut für Physik, Universität Potsdam, Am Neuen Palais 10, D-14469 Potsdam, BRD*
[2]*NASA Goddard Space Flight Center, Greenbelt MD 20771, USA*

Abstract. The Potsdam non-LTE code for expanding atmospheres, which accounts for clumping and iron-line blanketing, has been used to establish a grid of model atmospheres for WC stars. A parameter degeneracy is discovered for early-type WC models which do not depend on the 'stellar temperature'. 15 Galactic WC4-7 stars are analyzed, showing a very uniform carbon abundance (He:C = 55:40) with only few exceptions.

1. A grid of models for WC stars

The Potsdam non-LTE code, which accounts for complex model atoms, iron-group line blanketing and clumping (*cf.* Gräfener *et al.* 2002), has been employed to establish a grid of WC-type model atmospheres. The following parameters are kept constant for the whole grid: chemical composition He:C:O:Fe = 55:40:5:0.16 (by mass), luminosity $\log L/L_\odot = 5.3$, terminal wind velocity $v_\infty = 2000\,\mathrm{km\,s^{-1}}$, clumping factor $D = 10$. Grid variables are the stellar (effective) temperature T_* (referring to $\tau_{\mathrm{Ross}} = 20$), and the 'transformed radius' $R_t = R_*[v_\infty/(\dot{M}\sqrt{D})]^{2/3}$ (unit convention: v_∞ in $2500\,\mathrm{km\,s^{-1}}$, $\dot{M}$ in $10^{-4}\,M_\odot\,\mathrm{yr^{-1}}$, *cf.* Hamann & Koesterke 1998). For a fixed T_*, emission line equivalent widths of WR models depend to a good approximation only on R_t irrespective of different combinations of R_*, $\dot{M}$, v_∞ and D, while absolute fluxes scale with R_*^2.

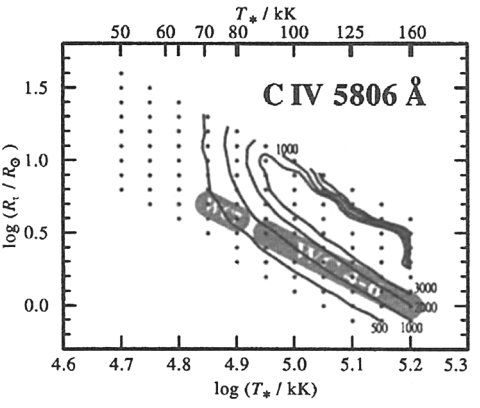

Figure 1. Grid of WC models: contours of equivalent widths for one specific spectral line (labels: $-W_\lambda$/Å). Small circles mark the calculated grid models. The grey bars indicate the location of the analyzed Galactic WC 4-6 ($T_* \gtrsim 90\,\mathrm{kK}$) and WC 7 ($T_* \lesssim 80\,\mathrm{kK}$) stars. Note that for the hotter part the contours almost align with the grey strip.

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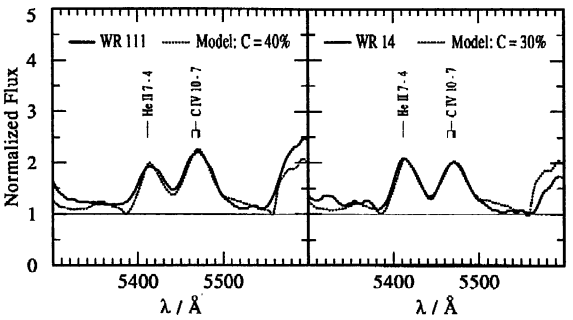

Figure 2. Determination of the carbon abundance from He II 5412 and C IV 5471. The observed spectrum (full line) of WR 111 is fitted by a model (dotted line) with He:C = 55:40 (by mass), while WR 14 shows less carbon (*right panel*).

The contours of equivalent widths in the $\log T_*$-$\log R_t$-plane (e.g. Figure 1) reveal a further degeneracy for hot, dense expanding atmospheres. For $T_* \gtrsim 100\,\mathrm{kK}$, the contours almost align with $R_t \propto T_*^{-2}$ (*cf.* the grey strip in Figure 1). This means that *early-type WC models basically depend on one single parameter only*, which we may define as

$$R_{\mathrm{t100kK}} = R_t \left(\frac{T_*}{100\,\mathrm{kK}}\right)^2 , \quad \text{implying} \quad R_{\mathrm{t100kK}} \propto L^{1/2} \left(\frac{\dot{M}\sqrt{D}}{v_\infty}\right)^{-2/3} .$$

Inspection of synthetic spectra confirms that they are indeed very similar for models with the same R_{t100kK}, irrespective of T_*. The physical reason is that in dense winds, *all* radiation (including continuum) arises from rapidly moving layers, and their location is determined by $\dot{M}$ alone. Note that the same R_{t100kK} implies the same ratio $L/\dot{M}^{4/3}$ (v_∞, D fixed).

2. Grid analysis of Galactic WC stars (12 WC 4-6 and 3 WC 7)

Spectra of 15 (putatively) single WC 4-7 stars were taken from own ESO and Calar Alto observations, the Torres & Massey (1987) atlas, and the *IUE* archive. The interstellar reddening is derived from fitting the spectral energy distribution. The line spectra of all WC 4-6 stars look amazingly similar. They all fall into the regime of parameter degeneracy ($T_* > 90\,\mathrm{kK}$), whereas the WC 7 stars are less hot ($T_* < 80\,\mathrm{kK}$). The coarse fits with grid models yield $\log R_{\mathrm{t100kK}} = 0.4$ with only small scatter, which implies $\log(L/\mathrm{L}_\odot) - \frac{4}{3}\log(\dot{M}/(\mathrm{M}_\odot\,\mathrm{yr}^{-1}) = 11.9$. Only four of the program stars have known distances, allowing for an estimate of their luminosity: $\log(L/\mathrm{L}_\odot) = 5.4$, 5.1, 5.2, 5.3 for WR 23, WR 111, WR 154 and WR 68, respectively. The helium/carbon abundance ratio is determined (*cf.* Figure 2). Again, most program stars are very similar and give a good fit with He:C = 55:40 (by mass) as chosen for the grid. Only four stars show slightly less carbon: WR 5 and WR 14: 30%; WR 17 and WR68: $\lesssim$30%.

References

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