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

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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 $v_\infty = 2000\,\mathrm{km/s}$, clumping factor $D = 10$. Grid variables are the stellar (effective) temperature T_* (referring to $\tau_\mathrm{Ross} = 20$), and the "transformed radius" $R_\mathrm{t} = R_*[v_\infty/(\dot{M}\sqrt{D})]^{2/3}$ (unit convention: v_∞ in 2500 km/s, $\dot{M}$ in $10^{-4}\,M_\odot/\mathrm{yr}$ – 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.

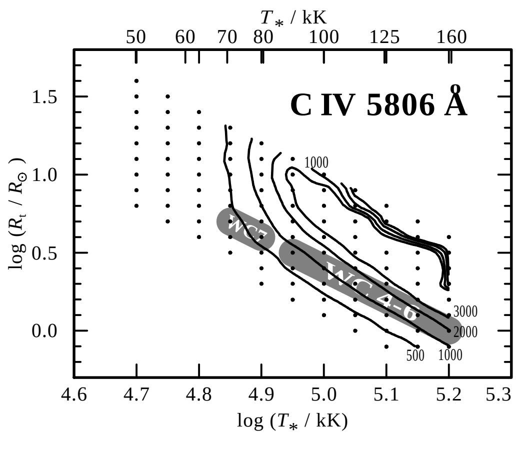

Figure 1. Grid of WC models: contours of equivalent widths for one specific spectral line (labels: $-W_\lambda/\text{Å}$). Small circles mark the calculated grid models. The grey bars indicate the location of the analyzed Galactic WC 4–6 ($T_* \gtrsim 90\,\mathrm{kK}$) and WC 7 ($T_* \lesssim 80\,\mathrm{kK}$)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

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

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

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 ($T_* > 90$ kK), whereas the WC 7 stars are less hot ($T_* < 80$ kK). The coarse fits with grid models yield $\log R_\mathrm{t100kK} = 0.4$ with only small scatter, which implies $\log(L/L_\odot) - \frac{4}{3}\log(\dot{M}/(M_\odot \mathrm{yr}^{-1}) = 11.9$. Only four of the program stars have known distances, allowing for an estimate of their luminosity: $\log L/L_\odot = 5.4, 5.1, 5.2, 5.3$ for WR 23, WR 111, WR 154 and WR 68, respectively. The helium/carbon abundance ratio is determined (cf. Fig. 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%.

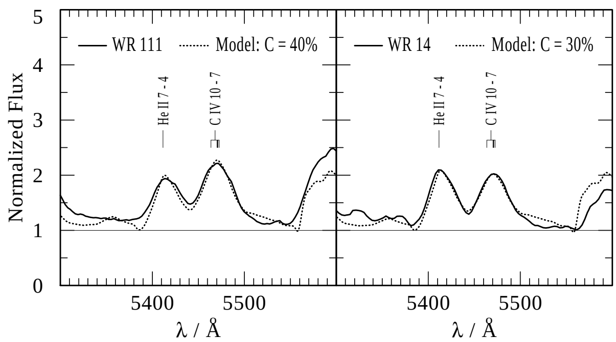

Figure 2. Determination of the carbon abundance from He II 5412 and C IV 5471. The observed spectrum (full line) of WR 111 is fitted by a model (dotted line) with He:C=55:40 (by mass), while WR 14 shows less carbon (right panel).

References

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