Stellar parameters of Wolf-Rayet stars from far-UV to mid-IR observations

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Abstract. Recent results for Galactic and Magellanic Cloud Wolf-Rayet stars are summarised based on line-blanketed, clumped model atmospheres together with UV, optical and IR spectroscopy. The trend towards earlier WN and WC spectral types with decreasing metallicity is explained via the sensitivity of classification diagnostics to abundance/wind density, such that WR mass-loss rates are metallicity dependent. Pre-supernovae masses for WC stars are determined, in reasonable agreement with CO-cores of recent Type Ic SN.

1. Recent observational and theoretical progress

This article will focus on recent determinations of physical parameters for Galactic and Magellanic Cloud WR stars from UV to IR diagnostics. Observationally, the *Far-Ultraviolet Spectroscopic Explorer* (*FUSE*) has provided an impressive database of λ 912 - 1187 Å spectroscopy for Galactic and Magellanic Cloud WR stars (see Willis *et al.* these Proceedings) to supplement previous UV datasets obtained with the *International Ultraviolet Explorer* (*IUE*) and *Hubble Space Telescope* (*HST*). At longer wavelengths, *Infrared Space Observatory* (*ISO*) observations of WR stars have now been analysed. Much of the recent observational progress with Wolf-Rayet stars has involved the acquisition of high quality optical spectroscopy for individual stars beyond the Magellanic Clouds (Drissen, these Proceedings), plus X-ray spectroscopy of single and binary WR stars (*e.g.*, Skinner *et al.* 2002), neither of which topics will be discussed here.

Theoretical developments in the last few years have been more steady, with the (laborious) implementation of line-blanketing into codes by elements other than CNO and Fe, which had already been discussed at the last hot star beach symposium, IAU Symp. No. 193 (van der Hucht *et al.* 1999). The major change has been the widespread use of such codes to analyse individual stars within a range of galaxies. At present, there are a variety of model atmosphere codes which consider sphericity and line blanketing and fall into two main types, outlined below.

CMFGEN (Hillier & Miller 1998) and the Gräfener *et al.* (2002) code make use of variants of the super-level approach to incorporate the effect of tens of thousands metal lines on the atmospheric structure within the radiative transfer code. CMFGEN can now simultaneously consider blanketing by individual ions of up to 30 elements, including C, N, O, Ne, Si, S, Ar, Ca, Fe and Ni (Hillier, these

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Table 1.   Recent revisions in the derived stellar parameters (clumped in bold with $f = 0.1$) for HD 165763 (WR 111, WC5) due to the incorporation of metal line-blanketing.

T_* kK	$\log L$ $L_\odot$	$\log \dot{M}$ $M_\odot \, yr^{-1}$	elements included	blanketing	reference
35	4.6	−4.6	He	no	Schmutz *et al.* 1989
59	5.0	−4.4	He, C	no	Hillier 1989
90	5.3	**−4.8**	He, C, O, Fe	yes	Hillier & Miller 1999
85	5.45	**−4.9**	He, C, O, Fe-group	yes	Gräfener *et al.* 2002

Proceedings), whilst Gräfener *et al.* consider CNO, Si plus Fe-group elements (Sc to Ni) grouped together in a single generic atom. This approach suffers the least number of approximations, but remains computationally demanding. Recent test calculations for early-type WC stars show (perhaps surprisingly!) good consistency between these two codes, including ionizing fluxes.

Alternatively, Schmutz (1997) and ISA-wind (de Koter *et al.* 1993, 1997) use separate codes to solve the radiative transfer problem and line blanketing, the latter making use of Monte Carlo techniques. The method had the great computational advantage that complete intensity-weighted effective opacity factors can be calculated separately from the transfer problem. On the negative side, the ionization and excitation equilibrium of metal species is approximate, dictating which lines are efficient at capturing photons for each point in the atmosphere. Test calculations for a late-type WN star between CMFGEN and ISA-wind show excellent agreement in derived stellar parameters, but rather poorer agreement for ionizing fluxes (Crowther *et al.* 1999).

The main effect of blanketing is to re-distribute extreme UV flux to longer wavelengths, reducing the ionization balance in the atmosphere, such that higher stellar temperatures (and luminosities) are required to match observed line profile diagnostics relative to unblanketed studies. This is illustrated in Table 1 for the prototypical Galactic early-type WC star HD 165763 (WR 111, WC5) whose derived stellar luminosity has increased by a factor of 5–7 over the past decade. Differences in luminosities for HD 165763 between the recent studies of Hillier & Miller (1999) and Gräfener *et al.* (2002) most likely result from the inclusion of additional blanketing elements, which CMFGEN now routinely handles. Recent revisions to temperatures and luminosities of O-type supergiants have acted in the opposite sense, relative to previous plane-parallel unblanketed model analyses, such that common techniques are now employed throughout for O-type and WR stars (*e.g.*, Crowther *et al.* 2002a,b).

Clumping is now routinely, albeit approximately, handled in WR model atmospheric studies via radial dependent volume filling factors, f. Constraints on f can be obtained from comparisons between red electron scattering wings and observations (*e.g.*, Hillier 1991), although exact determinations generally prove elusive due to line-blending, particularly in WC stars. Generally, $f \simeq 0.05 \text{-} 0.25$ provide reasonable matches to observed line profiles (*e.g.*, Hamann & Koesterke

1998), such that global mass-loss rates are reduced by a factor of $1/\sqrt{f} \simeq 2\text{-}4$ relative to smooth models. The majority of line profiles behave rather insensitively provided $\dot{M}/\sqrt{f}$ remains constant with some exceptions (*e.g.*, Herald *et al.* 2001). In WC stars, the line centre of UV resonance lines of C III-IV reacts to changes in f, providing additional constraints on the filling factor (Crowther *et al.* 2002a).

2. WN properties

Although large samples of WN stars have not yet been thoroughly analysed using recent line-blanketed codes, stellar temperatures of WN stars range from 30 kK (at WN10), to ~ 40 kK (at WN8) and approaching 100 kK for early-type WN (WNE) stars. Increased stellar temperatures, particularly for WNE stars, with correspondingly smaller radii, brings atmospheric models into much closer agreement with direct determinations from short period WN+O binaries, such as V444 Cyg (WR 139, WN5+O6III-V; *e.g.*, Moffat & Marchenko 1996). Clumped mass-loss rates from optical diagnostics generally lie in the range $\dot{M} = 10^{-5.5...-4.5} M_\odot \, \text{yr}^{-1}$. Mass-loss rates can also be obtained from radio determinations, although these too are subject to uncertainties in volume filling factors, and are limited to stars within a few kpc. Typical wind velocities span a wide range, well correlated with spectral type: $300 \, \text{km s}^{-1}$ at WN10 to $\sim 2000 \, \text{km s}^{-1}$ at WN3-4 (see *e.g.*, van der Hucht 2001, figure 5).

Relative to recent unblanketed results, Herald *et al.* (2001) obtained a smaller core radius and slightly enhanced luminosity for HD 96548 (WR 40, WN8) allowing for blanketing including Ne, Ar, Ca and Fe, such that the heavily blended Fe IV-V forest in the UV is very well reproduced. This naturally leads to the potential of late-type WN (WNL) stars as providing diagnostics of heavy elemental abundances from UV and far-UV (*FUSE*) spectroscopy. Morris *et al.* (2000) carried out a combined optical-infrared analysis of another WN8 star AS 431 (WR 147) revealing overall excellent consistency between visual, near-IR and mid-IR *ISO*-SWS line diagnostics, such that reliable stellar parameters may be obtained from solely IR observations, providing all necessary diagnostics are covered. Meanwhile, Crowther *et al.* (1999) used the H II ejecta nebula M1-67 as a sensitive diagnostic of the ionizing flux distributions predicted by analyses of the central star 209 BAC (WR 124, WN8) using CMFGEN and ISA-wind, favouring the former in this case.

In general, WNL stars are relatively H-rich (H/He $\simeq 0.5\text{-}2$ by number), whilst WNE stars do not contain hydrogen, although exceptions do occur. The question of whether weak-lined WN5–6 stars in R136 are moderately enriched in helium (H/He $\simeq 3$, Crowther & Dessart 1998) or unprocessed (H/He $\simeq 10$, de Koter *et al.* 1997) remains open. Where studies of WN stars have been carried out, N is extremely enriched and C depleted, consistent with CN-cycle processed material, with O generally more difficult to constrain (*e.g.*, Herald *et al.* 2001). In principal, other elemental abundances may be obtained from UV synthesis, but the most direct method is via analysis of mid-IR fine structure lines. Morris *et al.* (2000) obtained lower limits of ~ 0.5 solar for the abundance of Ne, S and Ca in AS 431 from *ISO* observations, with individual determinations

sensitive to the adoption of smooth or clumped winds (see *e.g.*, J.D. Smith, these Proceedings).

WN spectral types mimic underlying stellar temperatures rather well, at least within a particular (metallicity) environment. However, since WN subtypes depend on the relative strength of nitrogen emission lines, samples within different galaxies do not necessarily behave in the same manner. This is because N III-V classification lines have differing sensitivities to abundance which will be a factor of five times lower for a SMC WN star than its counterpart in the Solar neighbourhood. Crowther (2000) demonstrated that a WN5 star in the SMC would have a later spectral type in the Milky Way if its stellar parameters were kept *constant,* and an earlier spectral type at lower metallicity. This tendency broadly explains the observed trend earlier WN spectral types when one compares the statistics of WN stars in the Galaxy and Magellanic Clouds.

3.   WC properties

Due to the overwhelming effect of metal line-blanketing on the atmospheric structure of WC stars, considerable effort has recently gone into their analysis. Stellar temperatures range from $\sim 45\,$kK (WC9) to $\sim 60\,$kK (WC8) to $\sim 100\,$kK (WCE) and likely well in excess of this value for some WO stars. Mid-IR *ISO* observations (*e.g.*, De Marco *et al.* 2000) and far-UV *FUSE* spectroscopy (*e.g.*, Crowther *et al.* 2000) have been combined with the usual UV and optical diagnostics to derive stellar parameters. The use of similar techniques for Galactic (*e.g.*, Dessart *et al.* 2000) and Magellanic Cloud (Crowther *et al.* 2002a) WC stars permits their relative properties to be investigated in detail. Clumped WC mass-loss rates lie in the range $\dot{M} = 10^{-5.0\ldots-4.4}\,M_\odot\,\mathrm{yr}^{-1}$. As for WN stars, wind velocities are well correlated with spectral type: $1100\,\mathrm{km\,s}^{-1}$ at WC9, to $3000\,\mathrm{km\,s}^{-1}$ at WC4 (see *e.g.*, van der Hucht 2001, figure 5).

Carbon abundance determinations of WC stars have long used the He II $\lambda 5411$ and C IV $\lambda 5471$ recombination lines. However, conflicting results may result if limited model atoms are used, or if trace elements are neglected, such that Gräfener *et al.* (1998) obtained C/He $= 0.32$ by number (40% by mass) for HD 32125 (WC4), in contrast with the recent determination of C/He $= 0.13$ by number (25% by mass) from Crowther *et al.* (2002a). Carbon abundances in Galactic and LMC WC stars span a similar range, $0.1 \leq$ C/He ≤ 0.4, such that spectral types are *not* determined by carbon abundances, in conflict with predictions by Smith & Maeder (1991). Hamann *et al.* (these Proceedings) suggest a relatively uniform carbon abundance of C/He $\simeq 0.25$ for most Galactic WCE stars. Sand 2 (LMC, WO) does appear to have a higher C/He ratio than WC stars, but determinations for such stars are hindered by severe blending caused by its broad lines.

Oxygen abundances are rather more difficult to tightly constrain, since most diagnostics lie around $\lambda 3000$Å, and span a much wider range of ions – O III-VI in most WC stars – than carbon. Indeed, the classification line at $\lambda 5590$ is formed from a blend of O III and O V lines. Consequently, O/He determinations can generally not be obtained better than a factor of ~ 2. Oxygen in Galactic and LMC WC stars ranges from $0.02 \leq$ O/He ≤ 0.1, again with the probable exception of Sand 2 (Dessart *et al.* 2000; Crowther *et al.* 2000, 2002a). As for
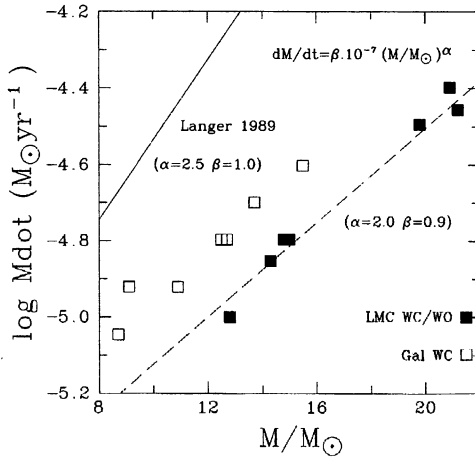
Figure 1. Comparison between WC masses and mass-loss rates for Galactic (open) and LMC (filled) stars derived by recent atmospheric calculations (see Crowther *et al.* 2002a) and the calibration of Langer (1989) for different α and β (see text)

WN stars, other elemental abundances are most readily determined from mid-IR fine structure lines, provided clumping factors can be determined. For γ^2 Vel (WR 11, WC8+O7.5III-V), Dessart *et al.* (2000) find that S is within 20 % of the cosmic value, whilst Ne is enhanced by a factor of ~ 8, in reasonable agreement with recent evolutionary predictions.

If WC spectral types do not result from chemical abundance variations, why are LMC WC stars systematically of earlier spectral type than Galactic WC stars? Temperature certainly plays a role, but for an answer we must first consider the WC classification lines — C III $\lambda 5696$ and C IV $\lambda\lambda 5801$-12 — in greater detail. The upper level of $\lambda 5696$ has an alternative decay via $\lambda 574$ with a branching ratio of 147:1. Consequently, $\lambda 5696$ only becomes strong when $\lambda 574$ is optically thick, *i.e.*, if the stellar temperature is low *or* the wind density is high. A comparison between Galactic WC5-7 stars and LMC WC4 stars reveals that their temperatures are comparable, such that the wind densities of the Galactic sample must be higher than the LMC stars. Crowther *et al.* (2002a) demonstrate that this is indeed the case, such that the principal difference amongst WCE stars is differing wind densities – high for WC6-7 stars and low for WC4 stars, with

$$\log(\dot{M}) = 1.38 \log(L/L_\odot) - 12.35 \qquad (1)$$

for the LMC stars, and Galactic WC stars $\sim$0.25 dex higher, in good agreement with the *generic* WR mass-loss luminosity calibration of Nugis & Lamers (2000).

4. A metallicity dependence for Wolf-Rayet stars?

A wind density origin for the subtype distribution amongst WC stars in Local Group galaxies can be understood if the mass-loss rates of Wolf-Rayet stars are metallicity dependent. The difference between Galactic and LMC WCE

stars amounts to only a factor of two, which is consistent with a metallicity dependence of $Z^{0.5-0.7}$ as predicted by radiation driven winds for O-type stars (*e.g.*, Vink *et al.* 2001). Reduced wind densities for WC stars at lower metallicity, preferentially affecting C III $\lambda 5696$, naturally explains the trend towards WC4 (and WO) stars, as is observed in the Magellanic Clouds and IC 10 (Crowther *et al.* these Proceedings). Although the atmospheres of WC stars are composed of mostly He, C and O, the heavier elements (Ne, Ar, Fe, Ni...) initiate their winds, as in O-typestars.

A WR metallicity dependence is not currently adopted in evolutionary calculations, which generally typically adopt $\dot{M} = \beta \times 10^{-7} (M/M_\odot)^\alpha$ for all H-free WR stars (Langer 1989). For WC stars Langer adopted $\alpha = 2.5$ and $\beta = 1.0$. This relationship is compared to recent mass-loss rates and masses for Galactic and LMC WC stars in Figure 1, revealing very poor agreement. LMC WC stars are well matched using $\alpha = 2.0$ and $\beta = 0.9$, similar to that discussed by Cherepashchuk (2001) from independent methods.

If WC stars are metallicity dependent, one would expect the same of WN stars. However, results to date for WN stars has been less clear (Crowther & Smith 1997; Hamann & Koesterke 2000), most likely due to greater scatter in wind properties at a given spectral type. Nevertheless, the trend is also towards weaker winds, as is seen most readily via the single WN stars in the SMC. The question of whether WR mass-loss rates are metallicity dependent has a major impact on the hardness of their ionizing flux distributions, as discussed by L.J. Smith *et al.* (these Proceedings). Denser winds cause softer Lyman continuum fluxes, which would imply that few WR stars produce nebular He II ionizing photons at high metallicity, with the opposite true at low metallicities.

5. Pre-supernova Wolf-Rayet masses

Recent theoretical progress in our analysis of Wolf-Rayet stars has led us to the claim that derived stellar parameters are 'robust'. Since there is a well established theoretical mass-luminosity relation for hydrogen-free WR stars, those which are members of close period binaries offer us the possibility to check derived spectroscopic luminosities. De Marco *et al.* (2000) obtained a stellar luminosity of the WC8 component of γ^2 Vel which implies a mass of $9\,M_\odot$ (via the Heger & Langer 1996 relationship), in remarkable agreement with $9.5\,M_\odot$ derived from the binary orbit.

We can employ evolutionary models to obtain remaining lifetimes, which together with an appropriate mass-loss luminosity relation (*e.g.*, Eqn. 1), permits an estimate of the final, pre-SN mass. This approach can be followed for all WR stars. However, uncertainties in evolutionary models and lack of recent results for WN stars suggest that WC stars represent our best candidates for the determination of pre-SN masses. Taking the LMC WC4 star HD 32402 (BAT99-11) as an example, Crowther *et al.* (2002a) derive a current mass of $21\,M_\odot$, a remaining lifetime in the range $1\text{-}4 \times 10^5\,\text{yr}$, and so a pre-SN mass of $14\,M_\odot$ (non-rotating model) or $19\,M_\odot$ (rotating model). From a sample of Galactic WC stars at known distance, final pre-SN masses lie in the range $7\text{-}14\,M_\odot$, *vs.* $11\text{-}19\,M_\odot$ using LMC stars.

A number of Type-Ic supernovae that have been studied in the past few years have probable WR precursors, including SN 1998bw, for which a CO (ejected) core mass of 13.8 $M_\odot$ was derived by Iwamoto *et al.* (1998). This agrees rather well with the expected pre-SN masses of LMC WC stars. There has been considerable interest in SN 1998bw since it was also GRB 980425. SN 2002ap is another nearby Type-Ic for which a WR star is one of the few likely progenitors (Smartt *et al.* these Proceedings). Unfortunately, most hypernovae or 'collapsar' models require rapid rotation, whilst rotation rates are lacking for almost all WR stars. The general consensus is that most WR stars have spun-down – indeed practically all WC stars are thought to be spherical, as inferred from spectropolarimetry of their winds (Harries *et al.* 1998).

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Discussion

HÖFLICH: GRB 980425 was dimmer than all other GRBs by a factor of 1000. Therefore, it may be dangerous to generalize the possible connection of GRB 980425 and SN 1998bw (SN Ic).

CROWTHER: I agree that this result should not be over-interpreted. However, it is the only case so far firmly connecting a likely WC SN Ic progenitor with a GRB.

MAEDER: You mention the fact that there are more WNE stars (zero or low H content) in the LMC than in the Milky Way, where more WNL (H present) are found. In this context, it is clear that the higher metallicity Z in the Milky Way implies more mass loss in the MS and thus the bare core characteristiscs of WR stars are revealed at an earlier stage of evolution (*i.e.*, when there is still H present). Basically, the initial Z (and mass loss rates) may influence the composition and luminosity ranges of WR stars, both in the WN and WC phases.

KUDRITZKI: Can you explain why the inclusion of metal opacity in the atmospheric models makes the WR stars significantly hotter than before?

CROWTHER: Put simply, since heavy element line-blanketing suppresses the UV fluxes at a given temperature and re-radiates at longer wavelengths *vs.* non-blanketed models. Therefore to maintain the He, N, C line diagnostics, one needs to increase the ionization balance or temperature.

LEITHERER: The metallicity range covered by observing WR stars at distances 3 kpc towards the Galactic Center and anti-center is about a factor of three. This is comparable to the difference of the solar neighborhood and LMC abundance. Do you observe different WR properties when you subdivide the galactic sample?

CROWTHER: This has not been systematically done, although abundances in such directions probably have considerable uncertainties. Most problematic for Galactic stars are reliable distances. Better progress is being made for extragalactic WR stars, where distances and metallicities are better constrained.

WALBORN: In connection with the Galactic abundance gradient and the pre-SN WR masses, I want to recall the WO2 object WR 102 (Sand 4) in the bizarre filamentary ring nebula G 2.4+1.4 toward the Galactic Center, studied a number of years ago by Dopita *et al.* (1990, ApJ 351, 563). It has an established initial mass of 60 $M_\odot$ and current mass of 5 $M_\odot$, presumably due to a higher metallicity than that of the solar

neighborhood.

LANGER: You suggest a metallicity dependence of WR winds, and you compare to the work of Nugis & Lamers, finding agreement. For WC stars, however, they predict a dependence of the mass loss rate in WC stars on the carbon abundance. With the carbon abundance being similar in Galactic and LMC stars, can this be conceivable with your results?

CROWTHER: The good agreement between galactic WC stars that Nugis & Lamers (2000) presented was for their 'generic' WR $\log(L\text{-}M)$ relation. This provided a better match to observations than their specific, C-dependent, relationship for WC stars.

MOFFAT: Since C and O come from nucleosynthesis, one might expect mass loss rates of WC stars to be independent of initial metallicity (unless wind driving is not so sensitive to C,O abundances).

CROWTHER: Wind driving in WC and WN stars has to depend on their heavy element abundances, analogous to O-type stars. C and O simply don't have enough driving lines in the necessary ionization potential range to make much difference, oblivious of their abundance.

The attentive audience. First row: Norbert Langer, Nolan Walborn, Cristina Cappa and Karel van der Hucht; second row: Lex Kaper, Tony Moffat, Gloria Koenigsberger, Katia Cunha and Verne Smith