Observed Metallicity Dependence of Winds from WR stars

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Abstract. A review of observational evidence in favour of a metallicity dependence of WR winds is presented. New near-IR studies of Milky Way, LMC and SMC early-type WN stars are presented, with weaker winds amongst WN stars containing hydrogen. A metallicity dependence is supported for WN stars with hydrogen, with $dM/dt \propto Z^\alpha$ with $\alpha \sim 0.8 \pm 0.2$. The influence of CNO content upon WN subtypes is discussed. Earlier WN spectral types are expected (and observed) at lower metallicity due to the abundance sensitivity of NIII-IV classification diagnostics. Recent physical and chemical results of WC stars in the Milky Way and LMC are discussed, suggesting a metallicity dependence of $\alpha \sim 0.6 \pm 0.1$. Earlier WC spectral types are predicted (and observed) in lower metallicity galaxies, due to the dependence of the CIII classification diagnostic on wind density. WO stars reveal lower wind velocities at lower metallicity, whilst the situation for WN and WC stars is unclear. Finally, the influence of a WR metallicity dependence upon the ionizing flux distributions and optical line luminosities is addressed, with particular regard to IZw 18. Weaker winds at low metallicity would imply harder ionizing flux distributions and lower line luminosities, arguing for an substantially increased number of WR stars with respect to standard calibrations, exacerbating difficulties with single star evolutionary models at very low metallicity.

1. Introduction

Wolf-Rayet (WR) stars represent the final stages in the evolution of the most massive stars, whose surface abundances trace the products of H (WN subtypes) and He (WC, WO subtypes) burning. They possess fast, dense winds, such that their spectroscopic appearance is dominated by characteristic broad, emission lines, with photospheric lines absent. Indeed, narrow-band imaging surveys of nearby galaxies have identified WR stars primarily via their emission lines (e.g. Hadfield et al. 2005), which can also be seen in the integrated spectra of a subset of star forming galaxies, known as WR galaxies.

Spectroscopically, WR stars are classified by the ratio of adjacent ions of nitrogen (WN), carbon (WC) or oxygen (WO), with high ionization in early subtypes, and low ionization in late subtypes (Smith, Shara & Moffat 1996; Crowther, De Marco & Barlow 1998). WN stars are also commonly subdivided into strong/weak or narrow/broad emission line stars. Observationally, earlier subtypes of both WN and WC stars dominate at low metallicities, a tendency which has been attributed to increased surface C+O abundances at lower metallicity for WC stars (Smith & Maeder 1991).
A metallicity dependence of the winds of massive O stars has long been established (e.g. Garmany & Conti 1985; Kudritzki, Pauldrach & Puls 1987), such that the observed population of WR stars are known to vary with environment (Maeder & Meynet 1994; Massey & Johnson 1998). In the Milky Way, with high main sequence mass-loss, WR stars are relatively common with N(WR)/N(O)~0.1 and N(WC)/N(WN)~1. In contrast, lower mass-loss prior to the WR phase in the Small Magellanic Cloud (SMC) causes a dramatic reduction in both the number of WR stars, N(WR)/N(O)~0.01, and their subtype distribution, N(WC)/N(WN)~0.1.

Up until recently, the winds of WR stars were assumed to be metallicity independent (Langer 1989). However, both observational (Crowther et al. 2002), and theoretical (Gräfener & Hamann 2005; Vink & de Koter 2005) studies have proposed a metallicity dependence, which have been incorporated into the latest evolutionary models (Meynet & Maeder 2005). Observational evidence in favour of a metallicity dependence is presented in this review. The question of metallicity dependent winds in WR stars has received considerable interest of late, since they represent the prime candidates for long-duration, soft Gamma Ray Bursts (GRBs), following the collapsar or hypernova scenario (Woosley, Eastman & Schmidt 1999). Consequently, the circumstellar environment of low metallicity GRBs is expected to differ substantially from those in metal-rich regions (Eldridge et al. 2006).

2. Physical and Chemical Properties

Prior to the development of non-LTE model atmosphere codes, the wind characteristics of WR stars were derived from their free-free excess following the technique of Wright & Barlow (1975) via mid-IR or radio observations, revealing high mass-loss rates of a few $10^{-5} M_\odot$ yr$^{-1}$. Indeed, radio mass-loss rates should be reliable providing the chemical composition and degree of ionization are appropriate to the radio forming continuum. Recent studies claiming reduced mass-loss rates for WC9 stars (e.g. Leitherer, Chapman & Koribalski 1997) are questioned by Crowther, Morris & Smith (2006) who argue that helium is partially neutral in the outer stellar wind.

Terminal wind velocities, most reliably measured from UV P Cygni lines (Prinja, Barlow & Howarth 1990) range from $\leq 1000$ km/s for late WN and WC subtypes to $\geq 3000$ km/s for early WC stars or even higher for WO stars (Kingsburgh, Barlow & Storey 1995). Terminal velocities can alternatively be obtained from optical emission lines, providing the wind has reached its maximum flow rate in the line forming region. This is generally true for stars exhibiting strong emission lines, but not for weak emission line stars, such as the WN stars in the SMC (Conti, Garmany & Massey 1989). Differences in WR subtype distributions in different host galaxies generally hinders efforts at establishing a metallicity dependence. Fortunately, the presence of WO stars in a wide variety of environments, from the inner Milky Way (e.g. Sand 4) to IC 1613 (Kingsburgh & Barlow 1995) permits studies of similar stars spanning an order of magnitude in metallicity. Fig. 1 compares wind velocities of all known WO stars, and indeed suggests lower wind velocities at low metallicity, despite small number statistics.
Hydrogen abundances in WN stars may be derived from the Pickering-Balmer series (Conti, Leep & Perry 1983) and support severe H depletion, whilst high carbon abundances of C/He ≥ 0.1 can be determined for early WC stars from recombination line theory (Smith & Hummer 1988).

The development of non-LTE model atmospheres by D.J. Hillier and W.-R. Hamann and coworkers during the 1980s and 1990s has permitted great progress via the determination of physical and chemical properties by spectral line fitting, via diagnostic lines of He and/or N in WN stars and He and/or C in WC stars. The latest versions of these codes typically treat non-LTE in a spherical, expanding, extended atmosphere considering the effects of metal line blanketing (CMFGEN: Hillier & Miller 1998; PoWR: Gräfener & Hamann 2005). Historically, O stars were analysed using plane-parallel codes (e.g. TLUSTY: Hubeny & Lanz 1995), whilst current models (e.g. FASTWIND, Puls et al. 2005) now also account for winds and line blanketing.

Clumping is incorporated into these codes following an approximate manner via a volume filling factor, \( f \), such that identical recombination line profiles – scaling with the square of the density – result if \( \dot{M}/\sqrt{f} \) is held constant. The primary diagnostics constraining clumping are the electron scattering wings, with a linear dependence upon density (Hillier 1991). The assumption of spherical symmetry appears to be reasonable for the majority of WR stars, since spectropolarimetric studies indicate only 5 out of 29 WR stars show any persistent line effect (Harries, Howarth & Hillier 1998). Stars which do reveal significant equator-to-pole density ratios of 2–3 tend to possess strong winds and span late WN (with hydrogen), early WN (no hydrogen) and WC subtypes.
4. Metallicity dependent WN winds?

Smith & Willis (1983) compared the properties of Large Magellanic Cloud (LMC) to Milky Way WR stars and concluded there was no significant differences between the two populations. These conclusions were supported by Koesterke et al. (1991) and later Hamann & Koesterke (2000) from detailed non-LTE modelling although a large scatter in mass-loss rates within each parent galaxy was revealed. One might conclude that there was no metallicity dependence, or that any differences are too subtle to be identified from the narrow metallicity range spanned by the Milky Way and LMC, given the multiple evolutionary channels available to stars entering the WN stage.

Crowther (2000) analysed the sole (at that time) single WN star in the SMC, Sk 41 (WN6ha). In comparison to LMC and Galactic late-type WN counterparts, Sk 41 was revealed to possess a low wind velocity and mass-loss rate. A larger sample of single low metallicity WN stars was needed for definitive conclusions regarding a metallicity dependence. This was provided by Foellmi,
Moffat & Guerrero (2003a) who concluded that many SMC WN stars which were hitherto considered to be binaries were apparently single. Observationally, SMC WN stars are well known to possess narrow, weak emission lines with respect to higher metallicity counterparts (Conti et al. 1989).

The strength of He\textsc{ii} $\lambda$4686 is related both to the wind density and ionization, whilst He\textsc{i} $\lambda 1.083\mu m$ is the primary wind density diagnostic in the optical/near-IR (Howarth & Schmutz 1992). In order to quantify the winds from weak-lined, single SMC stars with respect to Milky Way and LMC counterparts we have obtained near-IR spectroscopy from NTT/SofI for 4 SMC and 18 LMC WN3–6 stars from the samples of Foellmi et al. (2003ab) in collaboration with C. Foellmi and W. Vacca. In addition, near-IR spectroscopy of 8 Milky Way WN3–6 stars at known distances have been obtained by W. Vacca from IRTF/Spex.

We present CMFGEN results from our near-IR studies of WN stars in Fig. 2, where we have distinguished between stars containing surface hydrogen and those that do not. Luminosities (in $L_\odot$) range from $10^{4.8}$ to $10^{6.3}$ whilst mass-loss rates span $10^{-5.9}$ to $10^{-4.4} M_\odot$ yr$^{-1}$. It is apparent that the stars without hydrogen possess the strongest winds, with the exception of HD 192163 (Crowther & Smith 1996). The generic WN mass-loss luminosity relation of Nugis & Lamers (2000) for zero hydrogen content is indicated with exponent $dM/dt \propto L^{1.6}$, whilst a fit to our sample would suggest a softer dependence of $dM/dt \propto L^{0.6}$ suggesting less extreme mass-loss rates at the highest luminosities.

Since the number of Milky Way and LMC stars with atmospheric hydrogen is fairly small, we have fit the combined sample (excluding HD 192163), suggesting a dependence of

$$\log(M/M_\odot\text{yr}^{-1}) = 0.85 \log(L/L_\odot) - 9.93.$$  

It is apparent that the SMC stars possess even weaker winds. Assuming a similar luminosity dependence, one would require a $-0.4$ dex offset for the SMC stars ($1/5 Z_\odot$) with respect to the Milky Way/LMC stars ($1/2$ to $1 Z_\odot$), i.e. a metallicity dependence of $dM/dt \propto Z_\odot^\alpha$ with $\alpha \sim 0.8 \pm 0.2$. Note that negligible He\textsc{i} emission was observed for two SMC stars, such that an effective temperature of $\sim 85kK$ was adopted on the basis of the observed optical nitrogen spectrum, with the mass-loss rate resulting from He\textsc{ii} $\lambda 4686$ emission.

4. **Metallicity dependent WC winds?**

Gräfener et al. (1998) provided the first modern quantitative comparison between LMC and Milky Way WC stars, suggesting either a dependence of $dM/dt \propto L^{0.75}$ for the combined sample, or a steeper dependence for the Milky Way WC5–8 stars with $dM/dt \propto L^{1.5}$ with weaker winds for the LMC WC4 stars. Comparisons at still lower metallicity are hindered because the sole carbon-sequence member of the SMC is the WO binary Sand 1 (Sk 188).

Subsequently, Crowther et al. (2002) re-analysed the LMC WC4 sample of Gräfener et al. (1998) based on line blanketed models together with an increased sample of Milky Way stars which has been analysed in the same manner. Fig. 3 presents a comparison between the mass-loss rates and luminosities of Milky Way to LMC stars from Crowther et al. (2002), including HD 164270 (WC9) from Crowther et al. (2006). The early WC Milky Way stars closely follow the
Nugis & Lamers (2000) generic calibration, assuming C/He=0.2 and C/O=4 by number, whilst a fit to the LMC sample suggests a dependence of

$$\log(\dot{M}/M_\odot\text{yr}^{-1}) = 1.38 \log(L/L_\odot) - 12.35$$

i.e. revealing a similar slope to Nugis & Lamers (2000), albeit offset by –0.2 dex. Consequently, results for WC stars close to Solar metallicity suggest a $Z$ dependence with $dM/dt \propto Z^\alpha$, with $\alpha \sim 0.6 \pm 0.1$.

![Figure 3](image-url)

**Figure 3.** Comparison between mass-loss rates and luminosities of Milky Way (open) and LMC (filled) WC and WO stars, taken from Crowther et al. (2002, 2005). We include the Nugis & Lamers (2000) luminosity dependence (dotted line) for WR stars with composition C/He=0.2 and C/O=4 by number, plus the fit (solid line) to LMC stars by Crowther et al. (2002).

5. **Metallicity dependence of WR subtypes**

Empirically, the majority of WN stars in the Milky Way are late-type with N(WNL):N(WNE)~3:2 whilst those in the LMC and especially the SMC are early-type, with N(WNL):N(WNE)~1:5. Within the Milky Way most late-type stars contain hydrogen and most early-type stars do not, which is no longer true in the Magellanic Clouds. There are two atmospheric factors contributing towards the earlier subtypes at lower metallicities, namely the fixed CNO at a particular metallicity and the apparent decrease in wind strength with metallicity.
CNO compromises $\sim 1.1\%$ by mass of the Solar photosphere (Asplund et al. 2004) versus 0.48\% in the LMC and 0.24\% in the SMC (Russell & Dopita 1990). Since WN stars typically exhibit CNO equilibrium abundances, there is a clearly maximum nitrogen content available within a particular environment. Crowther (2000) demonstrated that for otherwise identical parameters, regardless of metallicity dependent mass-loss rates, a decreased nitrogen content at lower metallicity favours an earlier subtype, due to the strong abundance sensitivity of $\text{N}\text{III } \lambda 4634\text{–}41$ and weak sensitivity of $\text{N}\text{IV } \lambda 4058$.

If WN winds do scale with metallicity, one also expects earlier subtypes since high wind densities at high metallicities will efficiently cool the wind through metal lines (e.g. Hillier 1989), causing recombination from high ionization stages (e.g. $\text{N}^{5+}$) to lower ions (e.g. $\text{N}^{3+}$) close to the optical line formation region, which does not occur for low wind densities. Consequently, both factors favour late subtypes at high metallicity, and early subtypes at low metallicity, as generally observed.

The observational trend towards earlier WC subtypes at lower metallicity, together with early recombination line studies of early WC stars, led Smith & Maeder (1991) to suggest that early WC stars are more carbon-rich than late WC stars. Koesterke & Hamann (1995) analysed a large sample of Galactic WC5–8 stars, but did not confirm a subtype dependence. Crowther et al. (2002) supported the conclusions of Koesterke & Hamann, since the range of $(\text{C+O})/\text{He}$ abundances in LMC WC4 stars were similar to those of Milky Way WC5–8 stars.

Crowther et al. (2002) argued that weaker winds for early WC subtypes was the prime reason for a trend towards early subtypes at low metallicities. Indeed, their fig. 12 illustrated that at fixed stellar parameters and chemical composition, a reduction in mass-loss rate by only a factor of two causes a WC7 star to become a WC4 subtype. The cause of this dramatic shift is due primarily to the sensitivity of the classification line $\text{C}\text{III } \lambda 5696$ to mass-loss. Other $\text{C}\text{III}$ lines, such as $\text{C}\text{III } \lambda 6740$, are relatively insensitive to such modest changes in wind density. If early WC stars dominate at low metallicity, as is the case for the LMC, SMC and IC 10 (Crowther et al. 2003), one would expect that late WC stars dominate at high metallicity. Indeed, all 5 WR stars recently identified in the inner Milky Way by Hopewell et al. (2005) were of WC9 subtype. Hadfield et al. (2005) also found that WC8–9 subtypes dominate the WC population of the metal-rich spiral galaxy M 83.

6. Impact of weak WR winds at lower metallicity: I Zw 18

To date, several studies have identified WN and WC stars in the very metal poor ($1/50 Z_\odot$) galaxy I Zw 18. Izotov et al. estimated a total of 17 late WN stars plus 5 early WC stars, whilst WC populations were identified by Legrand et al. (1997) and Brown et al. (2002). This galaxy lies at 10–15 Mpc, so one has to infer individual properties from extrapolation of nearby, resolved WR populations.

Schmutz, Leitherer & Gruenwald (1992) stressed the importance of stellar wind density on the ionizing flux distributions of WR stars, such that emission at energies above the He$^+$ edge ($\lambda < 228\text{A}$) relies upon the WR wind being relatively transparent. High metallicity, strong winds will generally produce
Figure 4. Comparison between early WN CMFGEN models with fixed parameters (90kK, \( \log I/\lambda L_\odot = 5.6 \), \( v_\infty = 1900 \) km/s) except that the mass-loss rates (and metal abundances) differ by a factor of 15 (50). The high mass-loss rate model closely matches the spectrum of HD 50896 (WN4b, Morris et al. 2004) whilst the low mass-loss rate model might be representative of an early WN star in I Zw 18 (Crowther & Hadfield 2006).

Strong optical emission lines, though negligible hard ionizing radiation, while low metallicity, weak winds will conversely produce weak optical emission lines and prodigious hard ionizing radiation (Smith, Norris & Crowther 2002). Therefore, if low metallicity WR stars – such as those observed in I Zw 18 – do possess weak winds, they would be expected to possess (difficult to detect) weak emission lines, faint optical continua and hard extreme UV radiation. Indeed, strong nebular He II \( \lambda 4686 \) is observed in I Zw 18 whose origin may be due to WR stars.

To illustrate the effect of reduced wind density upon the ionizing flux distribution of WN models, Fig. 4 compares the rectified optical spectra and ionizing flux distributions for the line blanketed CMFGEN model of the strong-lined Galactic WN4b star HD 50896 (Morris, Crowther & Houck 2004) with an identical model, except that the elemental abundances have been reduced by a factor of 50, to mimic the abundances of I Zw 18, with the mass-loss rate reduced by a factor of \( 50^{0.7} \sim 15 \) from \( 3 \times 10^{-5} \) to \( 2 \times 10^{-6} \) \( M_\odot \) yr\(^{-1} \). It is apparent that the low metallicity WR star has a much harder ionizing flux distribution, with significant emission shortward of the He\(^+\) edge at 228Å. In addition, the weak wind model has a factor of 4 times smaller He II \( \lambda 4686 \) equivalent width, plus a factor of 5 times weaker optical continuum, such that the He II \( \lambda 4686 \) line luminosity is reduced by a factor of 20 relative to the Solar counterpart.
At present, average Milky Way/LMC WN and WC line luminosities are used to determine the number of WR stars in unresolved star forming regions at all metallicities (Schaerer & Vacca 1998). If individual WR line luminosities are lower at lower metallicity, this would imply a larger number of WR stars than is presently assumed. Empirically, Fig. 5 illustrates that indeed WN stars in the SMC do possess lower He\textsc{ii} $\lambda$4686 line luminosities than their counterparts in the LMC, by factors of 5 (early WN) or 4 (mid WN) on average (Crowther & Hadfield 2006).

De Mello et al. (1998) argued that allowing for the WC contribution to the blue WR feature in the observations of Izotov et al. (1997) would reduce the WN content to $\sim 4$ late-type stars, based on the standard line luminosity calibrations. If the WN stars observed in I Zw 18 are early WN stars, which are more common at lower metallicity, one would need to increase that total by a factor of up to $\sim 30$, to $\sim 120$ for their assumed distance. De Mello et al. (1998) claimed reasonable agreement between instantaneous burst models at $1/50Z_{\odot}$ with observations. This agreement would naturally be lost if the absolute number of WR stars was increased by such a large factor.

How would the properties of low metallicity, weak wind WC stars differ from those in the Milky Way? Fig. 6 compares a CMFGEN model for the LMC WC4 star HD 37026 from Crowther et al. (2002) with an identical model, except that the heavy element abundances (beyond Ne) have been reduced from $\sim 1/2 Z_{\odot}$ to $1/50 Z_{\odot}$ (I Zw 18), and the model mass-loss rate has been reduced by a factor of $25^{0.5} \sim 5$ from $3 \times 10^{-5}$ to $6 \times 10^{-6} M_{\odot}yr^{-1}$. As with the WN case,
the low mass-loss model displays an earlier spectral type (WO), and has a much harder ionizing spectrum, including significant emission shortward of the He$^+$ edge at 228Å. Indeed, some WO stars are associated with H II regions containing nebular He II λ4686 (e.g. DR1, Kingsburgh & Barlow 1995).

Observationally, WO stars, showing strong O VI-vi emission dominate at the lowest metallicities (SMC, IC 1613). Kingsburgh et al. (1995) demonstrated that WO stars exhibit high (C+O)/He abundances, which was confirmed by detailed modelling of the single LMC WO star Sand 2 by Crowther et al. (2000). Why are WO stars preferentially observed in low metallicity regions? Strong, carbon-rich winds very effectively recombine high ionization stages, such as OVI+, to lower ionization, e.g. OIV+ or OIII+, in the optical line formation region. One would therefore expect a dominant weak-lined WC or WO population in I Zw 18. Izotov et al. (1997) and Legrand et al. (1997) both identified broad (FWHM=50±10Å) C IV λλ5801–12 emission in I Zw 18 which they attributed to WC stars, whilst Brown et al. (2002) identified broad C IV λλ1548–51 emission, which they also attributed to WC stars. Neither of these observations preclude a WO origin, since their line widths are known to decrease in lower metallicity regions (recall Fig. 4). Indeed, the lowest known metallicity WO star, DR1 in IC 1613, has FWHM(C IV λλ5801–12) ∼70Å.
Metallicity dependent WR winds

We compare the observed C\textsc{iv} $\lambda\lambda5801$–12 line luminosities of single and binary WC4 and WO stars in Fig. revealing a factor of $\sim$3 times lower luminosity for WO stars. Indeed, the two WC models presented in Fig. differ by a factor of 6 in C\textsc{iv} $\lambda\lambda5801$–12 line luminosity. Consequently, if the I\textsc{zw} 18 carbon sequence WR stars are closer analogues of the WO stars, the number of stars would again need to be increased upwards, from $\sim$5 to $\sim$30 based on the observations of Izotov et al. (1997).

![Figure 7. Comparison between the C\textsc{iv} $\lambda\lambda5801$–12 line luminosities and equivalent widths for single (open) and binary (filled) WC4 and WO stars at known distance (Crowther & Hadfield 2006). All the WC4 stars are LMC members, whilst the WO stars are Sand 1 (SMC), Sand 2 (LMC) and Dr 1 (IC 1613) from Kingsburgh et al. (1995) and Kingsburgh & Barlow (1995). An estimate of line dilution is indicated for BAT99-10 (WC4+O).](image)

In summary, a natural consequence of metallicity dependent WR winds would be that the number of unresolved WR stars at low metallicities are presently severely underestimated by application of calibrations appropriate to LMC/Milky Way WR stars (Schaerer & Vacca 1998). If high spatial resolution observations of WR stars in I\textsc{zw} 18 reveal properties similar to Milky Way counterparts one would have to question their dependence on metallicity proposed here. Finally, reduced wind strengths from WR stars at low metallicities impacts upon the immediate circumstellar environment of long duration GRB afterglows, particularly since the host galaxies of high-redshift GRBs tend to be metal-poor (e.g. Chen et al. 2005).

Acknowledgments. The near-IR studies of WN stars presented here are in collaboration with Bill Vacca, Cedric Foellmi and Lucy Hadfield.

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