Reduced Wolf-Rayet line luminosities at low metallicity^{★,★★}

P. A. Crowther and L. J. Hadfield

Department of Physics & Astronomy, University of Sheffield, Hicks Building, Hounsfield Rd, Sheffield, S3 7RH, UK
e-mail: Paul.Crowther@sheffield.ac.uk

Received 3 October 2005 / Accepted 5 December 2005

ABSTRACT

New NTT/EMMI spectrophotometry of single WN2–5 stars in the Small and Large Magellanic Clouds are presented, from which He II $\lambda 4686$ line luminosities have been derived, and compared with observations of other Magellanic Cloud Wolf-Rayet stars. SMC WN3–4 stars possess line luminosities which are a factor of 4 times lower than LMC counterparts, incorporating several binary SMC WN3–4 stars from the literature. Similar results are found for WN5–6 stars, despite reduced statistics, incorporating observations of single LMC WN5–9 stars from the literature. C IV $\lambda 5808$ line luminosities of carbon sequence WR stars in the SMC and IC 1613 (both WO subtypes) from the recent literature are a factor of 3 lower than LMC WC stars from Mt Stromlo/DBS spectrophotometry, although similar results are also obtained for the sole LMC WO star. We demonstrate how reduced line luminosities at low metallicity follow naturally if WR winds are metallicity-dependent, as recent empirical and theoretical results suggest. We apply mass loss-metallicity scalings to atmospheric non-LTE models of Milky Way and LMC WR stars to predict the wind signatures of WR stars in the metal-poor star forming WR galaxy I Zw 18. WN He II $\lambda 4686$ line luminosities are 7–20 times lower than in metal-rich counterparts of identical bolometric luminosity, whilst WC C IV $\lambda 5808$ line luminosities are 3–6 times lower. Significant He⁺ Lyman continuum fluxes are predicted for metal-poor early-type WR stars. Consequently, our results suggest a larger population of WR stars in I Zw 18 than is presently assumed, particularly for WN stars, potentially posing a severe challenge to evolutionary models at very low metallicity. 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.

Key words. stars: Wolf-Rayet – galaxies: stellar content – galaxies: individual: I Zw 18 – stars: atmospheres

1. Introduction

Wolf-Rayet stars – subdivided into nitrogen (WN) and carbon (WC) sequences – are the evolved descendants of the O stars, and possess strong, broad, emission lines due to their dense, stellar winds. WR galaxies represent a subset of emission-line galaxies with active massive star formation via the direct signature of WR stars. To date, over a hundred WR galaxies are known in the nearby universe (Schaerer et al. 1999) via a broad C III $\lambda 4650$ /He II $\lambda 4686$ (blue bump) and/or C IV $\lambda 5808$ (yellow bump) emission features seen in the integrated optical spectrum of individual sources. Indeed, broad He II $\lambda 1640$ emission, attributed to WR stars, can be easily seen in the average rest-frame spectrum of $z \sim 3$ Lyman Break Galaxies (LBGs, Shapley et al. 2003).

The O star content of WR galaxies is typically derived indirectly using nebular hydrogen emission line fluxes to determine the total number of ionizing photons, from which the equivalent number of O7V stars is commonly calculated. The actual O star

content depends primarily upon the age and mass function, and relates to the equivalent number of O7V stars via a correction factor (Vacca 1994). As such, this quantity is fairly metallicity *independent*, although O7V stars at lower metallicity will likely have higher temperatures – and so higher Lyman continuum fluxes – than their high metallicity counterparts (Massey et al. 2005; Mokiem et al. 2006).

In contrast, the WR content is routinely obtained merely by dividing the observed emission bump fluxes, corrected for reddening and distance, by average line luminosities of Milky Way and Large Magellanic Cloud WR stars (Schaerer & Vacca 1998). As such, line luminosities of WR stars are *assumed* to be metallicity independent. Following this technique, the WR content of metal-rich (e.g. Mrk 309: Schaerer et al. 2000) and metal-poor (e.g. I Zw 18: Izotov et al. 1997) galaxies have been derived and compared, generally successfully, with evolutionary synthesis models.

Recent observational and theoretical evidence suggests WR winds depend upon the heavy metal content of the parent galaxy (Crowther et al. 2002; Gräfener & Hamann 2005; Vink & de Koter 2005). Since WR stars are believed to be the immediate precursors of some long-soft Gamma Ray Bursts

[★] Based on observations made with ESO Telescopes at the La Silla Observatory under programme ID 074.D-0696(A).

^{★★} Appendix A is only available in electronic form at <http://www.edpsciences.org>

(GRBs) the circumstellar environment of low metallicity GRBs is expected to differ substantially from those in metal-rich regions (Eldridge et al. 2005). If WR winds depend upon metallicity, do their line luminosities?

In the present study, we present new optical spectrophotometry of single, early-type WN stars in the Large and Small Magellanic Clouds in Sect. 2. The Magellanic Clouds were selected on the basis of their known distances, resolved stellar content and low interstellar reddenings. Indeed, reduced He II $\lambda 4686$ line luminosities for SMC WN stars ($\log O/H+12 \sim 8.1$) relative to the LMC ($\log O/H+12 \sim 8.4$) are obtained in Sect. 3, incorporating observations of late-type WN stars from the recent literature. We also demonstrate that carbon sequence WR stars at low metallicity – dominated by the rare WO subclass – also possess lower line luminosities than typical LMC counterparts based upon spectrophotometry of single and binary WC stars, published in part by Crowther et al. (2002). In Sect. 4, we consider whether reduced WR line luminosities are expected at lower metallicities for metallicity dependent WR winds. The results of our study are discussed in Sect. 5, with particular application to IZw 18, and brief conclusions are drawn in Sect. 6.

2. Observations of Magellanic Cloud WN stars

We present new spectrophotometry of single LMC and SMC early-type WN stars (Foellmi et al. 2003a,b). Photometric properties of 42 LMC and 7 SMC WN stars are presented in Table A.1 in the Appendix. LMC WR catalogue numbers include both Breysacher (1981, Br) and Breysacher et al. (1999, BAT99), for completeness, whilst SMC WR catalogue numbers follow Massey et al. (2003). The use of single stars at known distances permits a uniform method of deriving interstellar reddenings and line luminosities. In addition, average “generic” spectra may be obtained, of potential application in synthesising the bumps in Wolf-Rayet galaxies.

2.1. Observations and data reduction

We have observed our LMC and SMC sample using the ESO Multi Mode Instrument (EMMI) on the 3.5-m New Technology Telescope (NTT), La Silla, Chile. The detector consists of two 2048×4096 MIT/LL CCDs which were binned by a factor of 2 in both the spatial and dispersion direction. Data was acquired using the RILD (Red Imaging and Low Dispersion Spectroscopy) mode of EMMI with grism #3 ($2.8 \text{ \AA pixel}^{-1}$ dispersion) resulting in a wavelength coverage of $3800\text{--}9070 \text{ \AA}$ with a resolution of $9.3 \text{ \AA}$, as measured from comparison arc lines.

Conditions during data acquisition were photometric and seeing estimates varied between 0.6 and $1.1''$. These good conditions together with a wide, $5''$ slit suggests that complete transmission was achieved, and that the data are truly spectrophotometric. On-source exposure times ranged from 60 s for the brightest objects (e.g. BAT99-117) to 1260 s for the faintest (e.g. BAT99-23).

The data were reduced following the usual procedure i.e. bias subtracted, extracted and flux/wavelength calibrated using

packages within IRAF and STARLINK, except that flat fielding was not carried out due to spurious structure in all calibration frames. Care was taken during the extraction process to ensure the entire profile was extracted.

Absolute flux calibration was achieved by observing the spectrophotometric standard stars GD 50, GD 108, G 158-100 and Feige 110. A comparison between several standards taken at regular intervals during each night suggests that flux calibration of the data is accurate to $\pm 5\%$.

WN spectral types follow Foellmi et al., except for BAT99-50 and BAT99-73, which are revised from WN4 to WN5 on the basis that $N\text{ IV } \lambda 4058 \gg N\text{ V } \lambda 4610/N\text{ III } \lambda 4640$.

During the reduction of SMC-WR11 it became apparent that its spectrum was contaminated by a red line-of-sight companion ~ 1.2 arcsec to the west, which appears slightly brighter than the WR star in R -band acquisition images. We have extracted two apertures for this target: (i) the first provides spectrophotometry for the composite spectrum, but will overestimate the derived reddening because of the red companion; (ii) the second attempts to isolate the WN star, whose colours will provide a more robust reddening. Both entries are given for SMC-WR11 in Table A.1. The presence of a red companion naturally explains the unusually bright 2MASS JHK photometry for this star relative to other SMC WN stars.

2.2. Synthetic-Filter photometry

We have derived synthetic magnitudes for our LMC and SMC sample by convolving the calibrated spectra with *synthetic* Gaussian filters. The filters have central wavelengths of $\lambda_b = 4270 \text{ \AA}$, $\lambda_v = 5160 \text{ \AA}$ and $\lambda_r = 6000 \text{ \AA}$ and mimic the response of narrow-band b , v and r filters (Smith 1968; Massey 1984), with zero-points adopted that reproduce the synthetic magnitudes for the dataset of Torres-Dodgen & Massey (1988). In contrast with Schmutz & Vacca (1991), the intrinsic colours introduced in Sect. 2.3 include spectral lines, so we consider synthetic rather than monochromatic (line-free) magnitudes. An accuracy in the flux calibration of $\pm 5\%$ translates to a photometric uncertainty of ± 0.05 mag. As discussed above, synthetic magnitudes for SMC-WR11 are less reliable than other targets, due to its near neighbour.

Synthetic magnitudes and colours are presented in Table A.1, together with differences between this study and that published by Torres-Dodgen & Massey (1988). For the 31 LMC stars in common, we find satisfactory agreement between synthetic magnitudes and colours, with average differences of $\Delta v = v_{\text{EMMI}} - v_{\text{TM88}} = -0.13 \pm 0.21$ mag and $\Delta(b-v) = (b-v)_{\text{EMMI}} - (b-v)_{\text{TM88}} = -0.02 \pm 0.06$ mag, respectively. In a minority of cases differences were quite significant, with Δv for BAT99-37 and BAT99-128 differing by -0.86 and $+0.76$ mag, respectively. For these, Torres-Dodgen & Massey (1988) note that their results are uncertain due to non-photometric conditions. For the SMC sample, Torres-Dodgen & Massey only provide u and b magnitudes. For three WN stars in common, $\Delta b = b_{\text{EMMI}} - b_{\text{TM88}} = +0.12 \pm 0.04$ mag.

Fig. 1. Comparison between theoretical He II $\lambda 4686$ equivalent widths and $(b-v)_0$ colours from the Smith et al. (2002) grid of WN models of Solar, LMC and SMC metallicities with $40 \text{ kK} \leq T_* \leq 100 \text{ kK}$ (open symbols), together with a quadratic fit (solid line).

2.3. Interstellar reddening

Estimates of the interstellar reddening towards our sample have been derived from comparison between the observed colours and theoretical non-LTE model predictions, following Schmutz & Vacca (1991). Ideally, one would use $u-b$, but since our data did not extend far enough into the blue, we have instead based our reddening estimates on the standard $b-v$ colour index.

It is well known that non-LTE WR models with stronger emission lines display flatter optical continuum spectral energy distributions (Schmutz & Vacca 1991). Using the grid of WN non-LTE model spectra generated by Smith et al. (2002) for evolutionary synthesis calculations, we have derived the following approximate relationship between $(b-v)_0$ and the He II $\lambda 4686$ equivalent width, W_λ (in Å)

$$(b-v)_0 = -0.32 + 0.000476 W_\lambda - 4.2 \times 10^{-7} (W_\lambda)^2 \text{ mag}$$

which is presented in Fig. 1, together with individual data points from the $40 \text{ kK} \leq T_* \leq 100 \text{ kK}$ models for Solar, LMC and SMC metallicities. E_{B-V} followed from the standard relation $E_{B-V}/E_{b-v} = 1.21$ (Lundström & Stenholm 1984).

The scatter in the correlation between $(b-v)_0$ and $W_\lambda(4686)$ suggest that $(b-v)_0$ is accurate to ~ 0.04 mag. Combining this with the estimated uncertainty of ± 0.05 mag in the observed b and v colours, we expect that the typical uncertainty in derived E_{B-V} values will be $\sim \pm 0.06$ mag.

Derived E_{B-V} values for LMC and SMC WNEs are presented in Table A.1. We have compared reddening estimates for LMC WN stars to those published by Schmutz & Vacca (1991). For the 28 objects in common with both studies we find reasonable agreement, $\Delta E_{B-V} = E_{B-V}(\text{this study}) - E_{B-V}(\text{SV91}) = 0.07 \pm 0.08$ mag on average. For the SMC WN stars,

Massey & Duffy (2001) and Massey et al. (2003) assumed $(B-V)_0 = -0.32$ mag. Excluding SMC-WR11, which is contaminated by a red companion, we obtain $\Delta E_{B-V} = E_{B-V}(\text{this study}) - E_{B-V}(\text{MD01}) = -0.05 \pm 0.04$ mag.

With interstellar reddenings determined, we then fit Gaussian line profiles to individual He II $\lambda 4686$ emission lines using DIPSO (Howarth et al. 2003), revealing line fluxes, FWHM and equivalent widths, also presented in Table A.1. We assume a distance modulus of $\mu_{\text{LMC}} = 18.45 \pm 0.06$ mag (49 kpc), which represents the mean of 7 techniques discussed by Gibson (2000), and $\Delta\mu = \mu_{\text{SMC}} - \mu_{\text{LMC}} = 0.51 \pm 0.03$ mag, based upon three standard candle techniques (Udalski et al. 1999), implying $\mu_{\text{SMC}} = 18.96 \pm 0.07$ mag (62 kpc), in reasonable agreement with the recent eclipsing binary determination by Hilditch et al. (2005) of $\mu_{\text{SMC}} = 18.91 \pm 0.03$ mag. Line luminosities then follow from our derived reddenings and our assumed distances.

3. Reduced line luminosities of WR stars at low metallicity

3.1. He II $\lambda 4686$ in WN stars

It is well known that SMC WN stars possess relatively weak, narrow emission lines with respect to WN stars in the LMC and Milky Way (Conti et al. 1989). We now investigate whether their line luminosities also differ between these galaxies.

We have combined our NTT/EMMI datasets with mid to late-type LMC WN stars from Crowther & Smith (1997) uniformly degraded in spectral resolution to ~ 10 Å to mimic the EMMI datasets, supplemented by HST/FOS observations of R136a1, a2 and a3 (see Crowther & Dessart 1998).

Results for individual stars are presented in Fig. 2, where we compare He II $\lambda 4686$ line luminosities with equivalent widths (top) and FWHM (bottom). Figure 2 supports the conclusions of Conti et al. (1989) that SMC stars have weaker and narrower He II emission lines than their LMC counterparts for each WN subclass, although we have further restricted our sample to apparently single WN stars. This was primarily motivated to ensure a uniform method of deriving reddenings and line luminosities. Nevertheless, since our SMC sample comprises only seven WN stars in total, we have assessed the impact of including SMC WN binaries in our study. There are three additional WN3-4+O systems (SMC WR3, WR6, WR7) for which we have used the Torres-Dodgen & Massey (1988) spectrophotometry, plus reddening estimates from Crowther (2000). Their inclusion leads to a significant increase in the SMC WN2-4 average line luminosity. Nevertheless, it is clear that He II $\lambda 4686$ line luminosities of SMC stars are typically factors of 4-5 lower than their LMC counterparts for each WN subclass.

As previously discussed by Schaerer & Vacca (1998) there is a substantial scatter in the observed He II $\lambda 4686$ line luminosities of LMC WN stars. FWHM (He II $\lambda 4686$) clusters around ~ 28 Å for early WN stars in the SMC, whilst their LMC counterparts span a much broader range from 27-60 Å, although their mean (32 Å) is not so different from those in the SMC. Mean line luminosities for early (WN2-4),

Fig. 2. Comparison between the He II $\lambda 4686$ line luminosities of single LMC (open) and SMC (filled) early, mid and late-type WN stars versus equivalent width (*top*) and FWHM (*bottom*), supplemented by three SMC WN3–4 binaries (crosses). Data are taken from our NTT/EMMI datasets, supplemented by LMC late-type WN stars from Crowther & Smith (1997) and Crowther & Dessart (1998), uniformly degraded to the spectral resolution of EMMI (10 Å), explaining the deficiency at small FWHM. Data for the three SMC WN3–4 binaries are from Torres-Dodgen & Massey (1998), for which an estimate of the line dilution has been made on the basis of $M_v = -4$ mag for WR3 and $M_v = -5$ mag for WR6 and WR7 (Foellmi et al. 2003a), although we obtain $M_v = -3.9 \pm 0.7$ mag for our single SMC WN3–4 stars.

mid (WN5–6) and late (WN7–9) subtypes for each galaxy are presented in Table 1, where quoted uncertainties reflect the standard deviation on individual measurements, with values in parenthesis for early SMC WN stars additionally including binaries.

Our mean LMC WN2–4 He II $\lambda 4686$ line luminosity is $\sim 60\%$ higher than compiled by Schaerer & Vacca (1998), which was based on a reduced sample of LMC and Galactic stars, using inhomogeneous reddening and distance determinations. Our mean LMC WN5–6 and WN7–9 He II $\lambda 4686$ line luminosities straddle that determined by Schaerer & Vacca (1998) for Galactic/LMC WN6–9 stars (WN5 stars were excluded from their sample). Chandar et al. (2004) quote similar results using LMC results from Conti & Morris (1990). Vacca (1992) determined an average late-type WN line

Table 1. Mean optical line luminosities ($\pm$ standard deviations) of single Magellanic Cloud WN stars (units of 10^{34} erg/s). For comparison, Schaerer & Vacca (1998) obtained $5.2 \pm 2.7 \times 10^{35}$ erg/s and $1.6 \pm 1.5 \times 10^{36}$ erg/s for He II $\lambda 4686$ in Galactic/LMC WN2–4 and WN6–9 stars, respectively. Values in parenthesis additionally include three SMC WN3–4 binaries.

Line	WN2–4		WN5–6		WN7–9
	LMC	SMC	LMC	SMC	LMC
Number	36	5 (8)	15	2	9
N IV $\lambda 4058$	2 ± 2		26 ± 24	10 ± 9	17 ± 9
N V $\lambda 4603$ –20	16 ± 20	1.4 ± 0.9 (2.4 ± 2.1)			
N III $\lambda 4634$ –41			25 ± 27	4 ± 4	38 ± 19
He II $\lambda 4686$	84 ± 71	5.8 ± 3.4 (17 ± 16)	175 ± 166	43 ± 49	72 ± 67

luminosity of 1.7×10^{36} erg/s that is in good agreement with our WN5–6 mean, and represents a good match to that resulting for the 30 Doradus (LMC: Vacca 1992) and NGC 604 (M 33: Terlevich et al. 1996) complexes from direct WN star counts.

We have explicitly excluded HD 5980 (SMC WR5) from Fig. 2 and Table 1 since this 19.3 day WN+OB binary underwent an LBV eruption during 1994, with a B1.5Ia⁺ or WN11 spectral type during outburst (Barba et al. 1995). Indeed, the He II $\lambda 4686$ line in HD 5980 is highly phase-dependent as a result of strong excess emission arising from its wind-wind collision zone (Moffat et al. 1998).

Nevertheless, for completeness we have estimated its $\lambda 4686$ line luminosity from spectrophotometry of Torres-Dodgen & Massey (1988) plus our own AAT (RGO spectrograph) and Mt Stromlo 2.3 m (DBS spectrograph) observations from circa 1981–84 to 1997. Adopting an interstellar reddening of $E(B - V) = 0.07$ (Crowther 2000) we have estimated $\lambda 4686$ line luminosities of 5.5 – 15×10^{36} erg/s, unmatched during outburst by any Magellanic Cloud WN star. Koenigsberger et al. (2000) present UV spectroscopic observations between 1979 and 1999, also revealing a factor of ~ 3 increase in He II $\lambda 1640$ flux over that interval.

In addition, since our primary sample is drawn exclusively from single stars we have constructed “generic” early, mid and late WN optical spectra for each galaxy. Individual spectra were dereddened allowing for a uniform foreground Galactic (Seaton et al. 1979) extinction of $E(B - V) = 0.05$ mag, with the remainder according to either LMC (Howarth 1983) or SMC (Bouchet et al. 1985) extinction laws. The co-added average spectrum was subsequently scaled to the mean He II $\lambda 4686$ line luminosity, in each case. These are presented in Fig. 3, and reinforce the reduced line luminosities of SMC stars, relative to LMC counterparts for each WN subclass. For the SMC WN3–4 subtypes, the dotted spectrum in the region of He II $\lambda 4686$ additionally includes the three binaries SMC WR3, WR6 and WR7 in which we have attempted to take account of their O star continua by assuming Kurucz (1993) models adjusted such that $M_v = -4$ mag for WR3 and $M_v = -5$ mag for WR6 and WR7 following Fig. 16 of Foellmi et al. (2003a)¹. The generic

¹ Based upon our spectrophotometry and $E(B - V)$ values, we obtain $M_v = -3.9 \pm 0.7$ mag for single SMC WN3–4 stars.

Fig. 3. “Generic” UV and optical spectra of single, early (WN2–4), mid (WN5–6), and late (WN7–9) nitrogen sequence spectra for the LMC and SMC. The UV late WN spectrum is representative of WN8–9 stars, since no single WN7 stars have been observed with IUE/SWP. An additional spectrum for SMC WN3–4 stars (dotted lines) incorporates the binaries SMC-WR3, WR6 and WR7, for which an attempt has been made to correct for the continuum of the O star companion (see text).

spectra have potential use in synthesising the WR bumps in low metallicity star forming galaxies (e.g. Hadfield & Crowther, in preparation).

3.2. $\text{He II } \lambda 1640$ in WN stars

Since $\text{He II } \lambda 1640$ from WR stars is seen both in nearby starburst clusters (Chandar et al. 2004) and the average LBG spectrum (Shapley et al. 2003), what is the $\text{He II } \lambda 1640/\lambda 4686$ flux ratio of WN stars? Conti & Morris (1990) compared $F(\text{He II } \lambda 1640)/F(\text{He II } \lambda 4686)$ for a sample of LMC WN stars, revealing ~ 7.6 (see also Chandar et al. 2004). Schaerer & Vacca (1998) obtain 7.95 ± 2.47 and 7.55 ± 3.52 for early and late WN stars in the Milky Way and LMC.

29 LMC stars from our sample were observed with IUE/SWP using the large aperture (LAP) at low resolution (LORES), from which we have obtained an average

ratio of $F(\text{He II } \lambda 1640)/F(\text{He II } \lambda 4686)$ of 9.9 ± 3.2^2 . For 3 single SMC stars with low resolution, large aperture IUE SWP spectrophotometry, we obtain a similar average ratio of 11.9 ± 1.0 . Additionally, we have compared the theoretical $F(\text{He II } \lambda 1640)/F(\text{He II } \lambda 4686)$ ratio from the non-LTE model WN grid of Smith et al. (2002) discussed above, revealing 9–10 for SMC to Milky Way metallicities ($W_{\lambda 1640/4686} \sim 0.32$). Consequently, we suggest $F(\text{He II } \lambda 1640)/F(\text{He II } \lambda 4686) = 10 \pm 1$ for WN stars with metallicities between $1/5 Z_{\odot}$ and $1 Z_{\odot}$.

Generic ultraviolet early, mid, and late WN spectra for LMC metallicities are also included in the top panel of Fig. 3. These were obtained from IUE/SWP datasets, supplemented by HST/GHRS observations of R136a1, a2 and a3 for WN5–6 subtypes (Heap et al. 1994; Crowther & Dessart 1998), degraded to the low resolution IUE observations. Unfortunately, no single LMC WN7 stars have been observed with IUE/SWP, so our late-type WN average is drawn from solely WN8–9 stars. Since only a subset of our LMC WN sample possess ultraviolet spectroscopy, these have been adjusted relative to the generic optical WN spectra, such that $F(\text{He II } \lambda 1640)/F(\text{He II } \lambda 4686) = 10$.

3.3. $\text{C IV } \lambda 5808$ in WC stars

Do low metallicity WC stars also possess reduced line luminosities? Unfortunately, the only Local Group carbon sequence WR stars observed at metallicities below the LMC are the WO stars Sand 1 (Sk 188) in the SMC (Kingsburgh et al. 1995) and DR1 in IC 1613 (Kingsburgh & Barlow 1995). Smith et al. (1990a) established a uniform $\text{C IV } \lambda 5808$ line luminosity for LMC WC stars, which we now re-evaluate based upon a larger sample, and compared with low metallicity WO stars, plus Sand 2 in the LMC (Kingsburgh et al. 1995).

Spectrophotometry of 17 LMC WC stars were obtained with the Mt Stromlo 2.3 m Dual Beam Spectrograph (DBS) in Dec. 1997 (see Crowther et al. 2002 for details). For the 9 stars in common with Torres-Dodgen & Massey (1988), we find satisfactory agreement between synthetic magnitudes and colours, with average differences of $\Delta v = v_{\text{DBS}} - v_{\text{TM88}} = -0.05 \pm 0.05$ mag and $\Delta(b-v) = (b-v)_{\text{DBS}} - (b-v)_{\text{TM88}} = +0.04 \pm 0.14$ mag, respectively. Seven of our sample are single according to Bartzakos et al. (2001), i.e. the six studied by Crowther et al. (2002) plus MGWR5 (Morgan & Good 1985, alias BAT99–121). Reddenings are either from Crowther et al. (2002), $(b-v)_0 = -0.28$ mag for cases in which the WC star dominates the optical spectrum i.e. BAT99–121 and BAT99–70 (Brey 62), or $(b-v)_0 = -0.32$ mag otherwise. Smith et al. (1990a) assumed $(b-v)_0 = -0.30$ mag for all LMC WC stars, regardless of binarity. For the 7 stars in common, we find $\Delta E_{B-V} = E_{B-V}(\text{this study}) - E_{B-V}(\text{S90}) = -0.04 \pm 0.08$ mag. Photometric properties are presented in Table A.2 in the Appendix.

Average WC (LMC) and WO (LMC, SMC, IC 1613) line luminosities for the principal optical features are presented

² There is a marginal trend to a lower $\lambda 1640/\lambda 4686$ ratio from early-WN’s (10.8 , $\sigma = 3.2$, $N = 18$) through mid-WN’s (8.4 , $\sigma = 3.5$, $N = 7$) to late-WN’s (8.4 , $\sigma = 1.5$, $N = 4$).

Table 2. Mean line luminosities ($\pm$ standard deviations) for the strongest optical lines in single WC and WO stars in the Magellanic Clouds and IC 1613 (units of 10^{35} erg/s), assuming distances of 49 kpc, 62 kpc and 660 kpc to the LMC, SMC and IC 1613, respectively. For comparison, Smith et al. (1990a) adopted 3.2×10^{36} erg/s for C IV $\lambda 5808$ based on 5 LMC WC4 stars. Values in parenthesis additionally include WC+O binaries in the LMC and Sand 1 (WO+O) in the SMC.

Line	WC4	WO	WO
	LMC	LMC	SMC/IC1613
Number	7 (17)	1	1 (2)
O IV $\lambda 3411$	11.6 ± 4.6	9.1	13.3
	–		(27.7 ± 20.4)
O VI $\lambda 3818$	1.6 ± 0.6	5.5	15.1
	–		(20.0 ± 6.7)
C III $\lambda 4650$ /He II $\lambda 4686$	49.2 ± 22.7	5.2	8.6
	(48.8 ± 20.9)		(12.2 ± 5.0)
C IV $\lambda 5808$	33.6 ± 16.1	10.2	8.6
	(32.5 ± 15.8)		(11.3 ± 5.0)

in Table 2. Our results support the conclusions of Smith et al. (1990a) that the average C IV $\lambda 5808$ line luminosity of LMC WC stars is 3.2×10^{36} erg/s, using an increased sample. Despite the small number statistics, C IV $\lambda 5808$ line luminosities of WO stars are uniformly a factor of ~ 3 times lower than those of LMC WC stars.

Figure 4 compares the C IV equivalent widths and FWHM versus line luminosity, and includes an estimate of the line dilution for the multiple system BAT99-10 for which spatially resolved HST/FOS spectroscopy of the WC4 component has been obtained by Walborn et al. (1999, their HD32228-2). The figure further illustrates that WO stars in all low metallicity environments possess lower line luminosities than LMC WC stars. Ultimately, the robustness of these results depends on the universality of the empirical trend from WC to WO at low metallicity (see Sect. 4.2).

As with the WN sequence, we have constructed a “generic” LMC-metallicity early WC spectrum from our 7 single WC4 stars, which is presented in Fig. 5. This has potential use in synthesising the WR bumps in moderately metal-poor galaxies (Hadfield & Crowther, in preparation).

3.4. C IV $\lambda 1550$ in WC stars

We have derived the average C IV $\lambda 1550$ emission line flux of six LMC WC4 stars from HST/FOS observations presented in Gräfener et al. (1998) and Crowther et al. (2002), revealing $F(\text{C IV } \lambda 1550)/F(\text{C IV } \lambda 5808) = 6.0 \pm 0.6$, and $F(\text{He II } \lambda 1640)/F(\text{C IV } \lambda 1550) = 0.43 \pm 0.11$. These values agree with Schaerer & Vacca (1998) who obtained $F(\text{He II } \lambda 1640)/F(\text{C IV } \lambda 5808) = 2.14 \pm 1.09$ from 16 (mostly binary) WC4 stars. Sand 2 (WO) reveals similar values, with $F(\text{C IV } \lambda 1550)/F(\text{C IV } \lambda 5808) \sim 6.2$ and $F(\text{He II } \lambda 1640)/F(\text{C IV } \lambda 1550) \sim 0.25$. Figure 5 includes a generic ultraviolet LMC early-type WC spectrum,

Fig. 4. Comparison between C IV $\lambda 5808$ line luminosities of single (open) and binary (filled) WC4 (circles) and WO (triangles) stars in the LMC, SMC (Sand 1) and IC 1613 (DR1). WO observations are taken from Kingsburgh et al. (1995) and Kingsburgh & Barlow (1995), WC4 observations are from Mt Stromlo 2.3 m/DBS (see text). An estimate of line dilution is indicated for BAT99-10 (WC4+O) for which Walborn et al. (1999) have obtained spatially resolved HST/FOS blue spectroscopy of the WC4 component (their HD 32228-2).

which was obtained from the HST/FOS observations, scaled relative to the generic optical spectrum, such that $F(\text{He II } \lambda 1640)/F(\text{C IV } \lambda 5808) = 2.6$.

4. Role of metallicity-dependent WR winds

We have demonstrated that WR stars at sub-LMC metallicities possess reduced line luminosities, by factors of ≤ 3 (WC sequence) to 4–5 (WN sequence), with respect to higher metallicity counterparts of the same spectral subclass.

Up until recently, the winds of WR stars were assumed to be metallicity independent (Langer 1989). Crowther et al. (2002) claimed a metallicity dependence of WC winds from an analysis of LMC and Milky Way stars. Recently, Gräfener & Hamann (2005) have argued that line driving of WR winds is dominated by Fe-peak elements, whilst Vink & de Koter (2005) argue for $\dot{M} \propto Z^{0.86}$ for cool WN stars with $10^{-3} \leq Z/Z_{\odot} \leq 1$, where Z is the initial heavy metal content. For cool WC stars

Fig. 5. “Generic” UV and optical spectrum of an early WC star in the LMC.

Vink & de Koter (2005) propose $\dot{M} \propto Z^{0.66}$ for $0.1 \leq Z/Z_{\odot} \leq 1$, and $\dot{M} \propto Z^{0.35}$ for $10^{-3} \leq Z/Z_{\odot} \leq 0.1$.

In the following, we shall assume that WR winds scale with metallicity as $\dot{M}_{\text{WN}} \propto Z^{0.7}$ and $\dot{M}_{\text{WC}} \propto Z^{0.5}$, in part based on recent empirical results (Crowther 2006), for $10^{-2} \leq Z/Z_{\odot} \leq 1$. We now investigate how line luminosities and ionizing spectra from WN and WC stars vary with metallicity under such assumptions.

4.1. WN stars

We have selected HD 96548 (WN8) and HD 50896 (WN4) as representative single strong-lined Galactic late and early-type WN stars, for which spectroscopic analyses were performed by Herald et al. (2001) and Morris et al. (2004) based on the non-LTE, line blanketed model atmosphere code CMFGEN (Hillier & Miller 1998), which solves the radiative transfer equation in the co-moving frame, subject to the additional constraints of radiative and statistical equilibrium. New calculations are performed for the same ions considered by Herald et al. (2001) and Morris et al. (2004), with some subtle differences in atomic data.

We present the rectified synthetic UV and optical Solar-metallicity models of late- (hereafter WNL-1) and early-type (hereafter WNE-1) WN stars in Figs. 6 and 7, together with identical atmospheric models, except that the heavy metal content has been reduced from $Z_{\odot}$ to $1/50 Z_{\odot}$ and the mass-loss rate has been reduced by a factor of $50^{0.7}$ (hereafter WNL-2 and WNE-2). Although metal-poor WNE stars may be rich in hydrogen (e.g. Foellmi et al. 2003a) the actual hydrogen content does not significantly affect the ionizing flux or UV/optical spectrum, beyond the strength of the Balmer lines.

The low metallicity late-type WN model reveals a weak emission line spectrum, with primarily HeII $\lambda 4686$ and

Fig. 6. Comparison between late-type WN CMFGEN models in which parameters are fixed, except heavy metal abundances differ by a factor of 50, and mass-loss rates differ by a factor of $50^{0.7}$. The high mass-loss model closely matches the observed spectrum of HD 96548 (WN8, Herald et al. 2001) whilst the low mass-loss model may be representative of a low temperature WN star in IZ 18, with a WN5ha spectral type.

Fig. 7. Comparison between early-type WN CMFGEN models in which parameters are fixed, except heavy metal abundances differ by a factor of 50, and mass-loss rates differ by a factor of $50^{0.7}$. The high mass-loss model closely matches the observed spectrum of HD 50896 (WN4, Morris et al. 2004), whilst the low mass-loss model may be representative of a high temperature WN star in IZ 18, with WN2 spectral type.

NIV $\lambda 4058$ seen in the blue visual, such that the Solar-metallicity WN8 model has shifted to a weak-lined WN5ha subtype at low metallicity based on the Smith et al. (1996) classification scheme. Similarly, the low metallicity early-type WN model effectively displays a pure HeII emission line spectrum in the visual, such that the Solar-metallicity strong-lined WN4 model has shifted to a weak-lined WN2 subtype. In the ultraviolet, weak C and N features are seen in both cases. The principal physical parameters of each model are presented in Table 3.

The HeII $\lambda 4686$ line luminosity of model WNE-2 is severely reduced relative to WNE-1, due to the combination

Table 3. Physical parameters for the Solar metallicity late- and early-type WN models (WNL-1 adapted from Herald et al. 2001, WNE-1 adapted from Morris et al. 2004), together with the low metallicity models (WNL-2 and WNE-2), in which the metal content has been uniformly reduced to $1/50 Z_{\odot}$, and the mass-loss rate reduced by a factor of $50^{0.7}$. Clumping is incorporated via a volume filling factor $f = 0.1$ (Hillier 1991). Nitrogen and iron mass fractions are indicated. Line luminosities of He II $\lambda 1640$ and $\lambda 4686$ are listed (the 1640 line in the WNL-1 model is a blend). Q_0, Q_1, Q_2 are the number of ionizing photons shortward of the H⁰, He⁰ and He⁺ edges.

Model	WNL-1	WNL-2	WNE-1	WNE-2
T_* (kK)	45	45	90	90
$\log L/L_{\odot}$	5.60	5.60	5.60	5.60
$\log \dot{M}/M_{\odot} \text{ yr}^{-1}$	-4.5	-5.7	-4.5	-5.7
v_{∞} (km s ⁻¹)	850	850	1900	1900
$X(\text{H})$	15%	15%	0	0
$X(\text{N})$	1.2%	0.02%	1.2%	0.02%
$X(\text{Fe})$	0.12%	0.0024%	0.12%	0.0024%
M_* (mag)	-6.1	-5.3	-4.8	-3.2
L_{1640} (erg/s)	–	2.0×10^{36}	2.0×10^{37}	1.1×10^{36}
L_{4686} (erg/s)	1.6×10^{36}	2.2×10^{35}	2.0×10^{36}	1.1×10^{35}
$\log Q_0$	49.4	49.4	49.5	49.5
$\log Q_1$	48.4	48.9	49.15	49.25
$\log Q_2$	..	..	40.6	48.1
Sp Type	WN8	WN5ha	WN4	WN2

of reduced line equivalent width (factor of ~ 4) and reduced optical continuum flux (factor of ~ 5). The high wind density of the WNE-1 model prevents emission shortward of the He⁺ 228 Å edge, which is re-radiated at near-UV and optical wavelengths, as previously discussed by Schmutz et al. (1992) and Smith et al. (2002). In contrast, the low wind density of the low metallicity model WNE-2 produces a hard extreme UV flux distribution, as indicated in Fig. 8 (see also Table 3). Note that the empirical WN flux ratio $F(\text{He II } \lambda 1640)/F(\text{He II } \lambda 4686) = 10$ (Sect. 3.2) is also supported at low metallicity.

4.2. WC stars

We have carried out similar calculation for WC stars, based upon models for the single WC9 star HD 164270 in the Milky Way from Crowther et al. (2006, hereafter WCL-1) and the WC4 star HD 37026 (BAT99-52) in the LMC from Crowther et al. (2002, hereafter WCE-1). Once again, we have obtained CMFGEN model atmospheres for the same ions considered by Crowther et al. (2002, 2006) except for some subtle differences in atomic data. These calculations were repeated except that the heavy elemental abundances (beyond Ne) have been reduced from $1 Z_{\odot}$ (or $1/2 Z_{\odot}$) to $1/50 Z_{\odot}$ and reduced the mass-loss rate by a factor of $50^{0.5} \sim 7$ or $25^{0.5} \sim 5$, in order to mimic late- and early-type WC stars in IZw 18 (hereafter WCL-2 and WCE-2).

The reduced metallicity synthetic spectra reveal weak-lined WC spectral types, since the assumed C and O abundances

Fig. 8. Comparison between predicted emergent spectral energy distributions (erg cm⁻² s⁻¹ at 1 kpc) of late-type (*left panel*) and early-WN (*right panel*) CMFGEN models, with identical parameters except that heavy metal abundances differ by a factor of 50, and mass-loss rates differ by a factor of $50^{0.7} \sim 15$, such that the reduced mass-loss models (dotted, red in the electronic version) display harder flux distributions than the high mass-loss cases (solid, black in the electronic version).

Fig. 9. Comparison between late-type WC CMFGEN models in which parameters are fixed, except the heavy metal abundances differ by a factor of 50, and mass-loss rates differ by a factor of $50^{0.5} \sim 7$. The high mass-loss model closely matches the observed spectrum of HD 164270 (WC9, Crowther et al. 2006) whilst the low mass-loss model may be representative of a late-type WC star in IZw 18, with spectral type WC7.

remain high in the reduced metallicity models: WC7 in the case of WCL-2, and WC4 in the case of WCE-2 following the classification schemes of Crowther et al. (1998) or Smith et al. (1990b). O IV $\lambda 3411$ and O V $\lambda 5592$ are strong in WCE-2, with O VI $\lambda 3818$ weak. Note a modest increase in temperature to 110 kK is sufficient to produce strong O VI $\lambda 3818$ emission via a switch in the oxygen ionization balance, i.e. a WO subtype.

The low wind density WC models reveal spectral morphologies quite distinct from the high wind density cases, despite identical (C+O) abundances. Efficient metal wind cooling in the WCL-1 and WCE-1 models (Hillier 1989) produces strong C III lines. For example, C III $\lambda 4650$ dominates the $\lambda 4650$ feature in the WCE-1 model, with

Table 4. Physical parameters for the Solar metallicity late-type and LMC metallicity early-type WC models (WCL-1 adapted from Crowther et al. 2006, WCE-1 adapted from Crowther et al. 2002), together with the low metallicity models (WCL-2 and WCE-2), in which the metal content has been uniformly reduced to $1/50 Z_{\odot}$, and the mass-loss rate reduced by factors of $50^{0.5}$ (Solar to IZw 18) and $25^{0.5}$ (LMC to IZw 18). Clumping is incorporated in all models via a volume filling factor $f = 0.1$. Carbon, oxygen and iron mass fractions are indicated. Line luminosities of C IV $\lambda 1550$ (blended in WCL-1), $\lambda 5808$ (blended with C III $\lambda 5826$ in WCL-1) and C III $\lambda 5696$, $\lambda 4650$ /He II $\lambda 4686$, are listed. Q_0, Q_1, Q_2 are the number of ionizing photons shortward of the H^0 , He^0 and He^+ edges.

Model	WCL-1	WCL-2	WCE-1	WCE-2
T_* (kK)	50	50	100	100
$\log L/L_{\odot}$	4.90	4.90	5.65	5.65
$\log \dot{M}/M_{\odot} \text{ yr}^{-1}$	-5.0	-5.8	-4.5	-5.2
v_{∞} (km s $^{-1}$)	1050	1050	2900	2900
$X(C)$	35%	35%	44%	44%
$X(O)$	5%	5%	9%	9%
$X(Fe)$	0.12%	0.024%	0.06%	0.0024%
M_* (mag)	-4.6	-3.4	-4.8	-3.4
L_{1550} (erg/s)	..	7.2×10^{35}	2.5×10^{37}	5.1×10^{36}
L_{4650} (erg/s)	3.6×10^{35}	2.6×10^{35}	7.0×10^{36}	3.5×10^{35}
L_{5696} (erg/s)	5.6×10^{35}	2.2×10^{34}	–	–
L_{5808} (erg/s)	1.1×10^{35}	3.9×10^{34}	2.5×10^{36}	4.0×10^{35}
$\log Q_0$	48.6	48.8	49.5	49.5
$\log Q_1$	40.4	48.0	49.0	49.2
$\log Q_2$	..	..	..	47.5
Sp Type	WC9	WC7	WC4	WC4

$F(C \text{ III } \lambda 4650) \geq F(He \text{ II } \lambda 4686) \geq F(C \text{ IV } \lambda 4659)$. In contrast, cooling is greatly reduced in the low metallicity models, such that negligible C III emission is now predicted in the WCE-2 model, with $F(He \text{ II } \lambda 4686) \sim F(C \text{ IV } \lambda 4659)$ contributors to the $\lambda 4670$ feature. Consequently, typical line ratios of individual WC stars at LMC or Solar metallicity – e.g. $C \text{ III } \lambda 4650/C \text{ IV } \lambda 5805 \sim 1.6$ for WC4 stars (Smith et al. 1990a) – do not necessarily hold for WC stars in metal-poor environments. Indeed, one anticipates the need for a new system of WR spectral classification at low metallicity, based upon a set of standard stars, as in the Solar metallicity case.

Similar arguments to those discussed above for WN stars cause the C IV $\lambda 5808$ line luminosity of the low metallicity models to be reduced by factors of 3–6 relative to the Solar/LMC models, due to the combination of reduced line equivalent widths and reduced optical continuum fluxes. As before, the low metallicity, low wind density models predict much harder ionizing flux distributions than their high metallicity, high wind density counterparts from an observer’s perspective as indicated in Fig. 11 (see also Table 4).

5. Discussion

We have demonstrated that line luminosities of early–mid WN stars in the LMC exceed those in the SMC by ~ 4 –5.

Fig. 10. Comparison between early-WC CMFGEN models in which parameters are fixed, except heavy metal abundances differ by a factor of 25, and mass-loss rates differ by a factor of $25^{0.5} \sim 5$. The high mass-loss model closely matches the observed spectrum of the LMC WC4 star HD 37026 (Crowther et al. 2002), whilst the low mass-loss model may be representative of an early-type WC star in IZw 18, with WC4 or WO spectral type.

Fig. 11. Comparison between predicted emergent spectral energy distributions (erg cm $^{-2}$ s $^{-1}$ at 1 kpc) of late-type (*left panel*) and early-type (*right panel*) WC CMFGEN models, with identical parameters except that heavy metal abundances differ by a factor of 25–50, and mass-loss rates differ by factors of $Z^{0.5}$, such that the reduced mass-loss models (dotted, red in the electronic version) display harder flux distributions than the high mass-loss cases (solid, black in the electronic version).

If this is supported for other metal-poor galaxies, one would need to apply such a corrective factor when determining WR populations at low metallicity. Unfortunately, within the Local Group only NGC 6822 and IC 10 – with $\log (O/H)+12 \sim 8.25$ (Pagel et al. 1980; Garnett 1990) – possess metallicities comparable to the SMC. To date, only 4 and 11 WN stars have been confirmed in these respective galaxies (Massey & Johnson 1998; Crowther et al. 2003) whilst spectrophotometry is not yet available, preventing robust line flux comparisons since reliable reddening corrections rely upon accurate colours of isolated WR stars.

We propose that a correction factor may need to be applied when estimating WR populations from observations of unresolved clusters/galaxies at sub-LMC metallicities, where *adopted* values from metal-rich WR calibrations may greatly exceed those of individual stars within those galaxies. In the extreme case of IZw 18, our test calculations suggest factors of ~ 5 – 20 may be appropriate.

5.1. WR population of IZw 18 from optical studies

Izotov et al. (1997) and Legrand et al. (1997) presented observations of IZw 18-NW in which broad blue (C III $\lambda 4650$ /C IV $\lambda 4658$ /He II $\lambda 4686$, $FWHM \sim 70$ Å) and yellow (C IV $\lambda 5808$, $FWHM \sim 50$ Å) emission features were observed, together with nebular He II $\lambda 4686$ emission. Izotov et al. derived blue and yellow line luminosities of 4.8×10^{37} erg/s and 2.1×10^{37} erg/s, respectively, for a revised distance of ~ 14.1 Mpc (Izotov & Thuan 2004). Applying our own LMC WC calibration or that from Smith et al. (1990a) to the yellow feature would require ~ 7 equivalent WC4 stars (De Mello et al. 1998). In contrast, with a typical low metallicity WC star contributing a factor of ~ 5 less C IV $\lambda 5808$ flux, we suggest a much larger WC population of ≥ 30 may be necessary to explain the observed line flux in IZw 18. Depending upon individual temperatures, these stars would display either a weak-lined early WC, or a WO spectrum.

Legrand et al. (1997) noted that the observed line width of the C IV feature more closely matches that of LMC WC4 stars than WO stars (recall Fig. 4). However, WO stars are known to display decreasing wind velocities at lower metallicity, as demonstrated in Fig. 12. Consequently, one might expect low metallicity WO stars to have unusually narrow lines with respect to their metal-rich counterparts.

Izotov et al. noted that the C III-IV $\lambda 4650$ flux far exceeded that expected from the number of WC stars inferred from C IV $\lambda 5808$, assuming they were typical of LMC WC4 stars, which they exclusively attributed to He II $\lambda 4686$ in late-type WN stars. If WC stars in IZw 18 mimic those of the LMC one would expect C III-IV $\lambda 4650$ /C IV $\lambda 5808 = 1.5$ – 1.6 (Table 2; Smith et al. 1990a) so these would provide $\sim 2/3$ of the C III-IV $\lambda 4650$ flux observed by Izotov et al. (1997). The remainder could be attributed to ~ 10 WN5–6 stars, or ~ 20 WN7–9 (or WN2–4) LMC-like stars (Table 1; see also De Mello et al. 1998).

We have shown that low metallicity WC stars are likely to possess rather different ratios of C III $\lambda 4650$ to C IV $\lambda 5808$ line fluxes from near-Solar counterparts, so we advise caution when indirectly inferring WR populations at extremely low metallicities in this way. Observationally, it is challenging to establish the presence of WN stars in the Izotov et al. (1997) dataset since the $\lambda 4650$ feature is much broader than in late-type WN stars, with $FWHM \sim 70$ Å. Late-type LMC metallicity WN stars possess $FWHM \sim 20$ Å, at comparable spectral resolution (Fig. 2).

The difficulty in spectroscopically identifying WN stars in IZw 18 is almost certainly due to the extremely low He II $\lambda 4686$ line luminosity of individual WN stars, owing to

Fig. 12. Comparison between wind velocities of all known Local Group WO stars, from Kingsburgh et al. (1995), Kingsburgh & Barlow (1995) and Drew et al. (2004). For Milky Way WO stars we have adopted $\log(O/H)+12 = 8.6$ for WR30a which lies beyond the Solar circle, 8.7 for Sand 5 which lies at the Solar circle and 8.8 for Sand 4 and WR93b which lie within the Solar circle.

the steeper metallicity dependence of their winds relative to WC stars (Vink & de Koter 2005). Since late-type WN stars positively shy away from low metallicity environments (recall Fig. 6), line luminosities of individual mid-type or early-type WN stars in IZw 18 may be a factor of ~ 10 times smaller than for LMC late-type WN stars as determined by Schaerer & Vacca (1998). Indeed, if we assume $\sim 1/3$ of the C III-IV $\lambda 4650$ flux observed by Izotov et al. (1997) is due to SMC early-type WN stars, we would require 100–300 WN stars, depending upon whether we adopt average values from Table 1 including or excluding the WN+O binaries. Consequently, large numbers of WN stars would be required for their spectroscopic detection via broad He II $\lambda 1640$ or $\lambda 4686$ emission. Alternatively, their presence in smaller numbers may be seen indirectly via strong nebular He II $\lambda 4686$ emission, which is indeed observed in IZw 18.

5.2. WR population of IZw 18 from UV studies

Brown et al. (2002) scanned the NW part of IZw 18 with HST/STIS, revealing two clusters, exhibiting strong C IV $\lambda 1550$ and He II $\lambda 1640$ emission. Adjusting their fluxes to a distance of 14.1 Mpc (Izotov & Thuan 2004) indicates He II $\lambda 1640$ luminosities of $L_{1640} = 3.0 \times 10^{37}$ erg/s and 4.0×10^{37} erg/s, respectively. Brown et al. applied the Schaerer & Vacca (1998) He II $\lambda 1640$ calibration of a representative Milky Way WC5 star, implying 6 and 8 WC stars, respectively, with $N(WC)/N(O) \sim 0.2$ in the former cluster.

A similar exercise for the (distance adjusted) C IV $\lambda 1550$ luminosities of $L_{1550} = 6.9 \times 10^{37}$ erg/s and 2.8×10^{37} erg/s

would lead to 3–4 and 1–2 stars, respectively, according to Sect. 3.4 assuming representative LMC-type WC4 stars. The reduced numbers with respect to Brown et al. (2002) is due to the higher line luminosities of LMC WC4 stars relative to Milky Way WC5 stars, plus the low $\lambda 1550/\lambda 1640$ ratio of ~ 0.7 for the second cluster, suggesting a primary contribution by WN stars rather than WC stars.

If we instead assume a representative C IV $\lambda 1550$ line luminosity of 4×10^{36} erg/s for a single WC star in IZw 18, i.e. 5 times lower than typical LMC WC4 stars, we would require ~ 17 and ~ 7 weak-lined WC stars for the two clusters. Brown et al. remarked upon their unusually high $N(\text{WR})/N(\text{O})$ populations, which would be exacerbated if larger WC populations are inferred at reduced metallicities.

5.3. Challenges for evolutionary models of single massive stars at low metallicity

The potential presence of much greater numbers of WR stars in IZw 18 than is currently appreciated naturally causes problems for evolutionary models of single massive stars at low metallicity. Non-rotating, high mass-loss evolutionary models were calculated by de Mello et al. (1998), revealing progression through to the WN and WC phases for stars of initial mass $\sim 90 M_{\odot}$ and $120 M_{\odot}$, respectively. For an instantaneous burst with a Salpeter IMF and an upper mass limit of $\sim 150 M_{\odot}$ the maximum $N(\text{WR})/N(\text{O})$ ratio is ~ 0.02 , with WN stars dominating the WR population, i.e. $N(\text{WC})/N(\text{O}) \leq 0.003$. In the case of a WR population with ~ 30 WC or WO stars, and potentially ~ 200 WN stars, one would obtain $N(\text{WC})/N(\text{O}) \sim 0.02$ and $N(\text{WN})/N(\text{O}) \sim 0.1$ in IZw 18, based upon the ~ 2000 O star content from Izotov et al. (1997, again adjusted to a distance of 14.1 Mpc) greatly exceeding evolutionary predictions for single stars. Further comparison awaits the calculation of evolutionary models for single stars at very low metallicity including rotation and contemporary mass-loss rates.

5.4. Circumstellar environment of long duration GRBs

Within the past decade, several long duration (≥ 2 s) GRBs have been positively identified with Type Ic core-collapse SN (Galama et al. 1998; Stanek et al. 2003), supporting the collapsar model of MacFadyen & Woosley (1999) involving Wolf-Rayet stars. The ejecta strongly interacts with the circumstellar material, probing the immediate vicinity of the GRB itself, thus providing information on the progenitor (Li & Chevalier 2003; van Marle et al. 2005).

If WR stars possess metallicity-dependent winds, one would potentially expect rather different environments for the afterglows of long-duration GRBs, that were dependent upon the metallicity of the host galaxy. WN stars in a galaxy of $1/100 Z_{\odot}$ may possess wind densities a factor of ~ 25 times lower than those in the Milky Way. In general, the metallicity dependence of wind velocities for WR stars is unclear, although amongst carbon sequence WR star, lower velocity winds are seen in WO stars from metal-poor environments (Fig. 12).

Overall, the immediate environment of GRBs that involve Wolf-Rayet precursors may differ substantially from those of Solar metallicity WR stars (Eldridge et al. 2005). Indeed, the host galaxies of high-redshift GRBs tend to be rather metal-poor, from medium to high resolution spectroscopy obtained immediately after the burst. For example, Vreewijk et al. (2004) suggest $1/20 Z_{\odot}$ for the host galaxy of GRB 030323 at $z = 3.37$ and Chen et al. (2005) conclude $1/100 Z_{\odot}$ for the host galaxy of GRB 050730 at $z = 3.97$.

6. Summary

We have demonstrated empirically that individual WN and WC stars at SMC metallicities possess lower optical line luminosities than those in the LMC (or Milky Way), which currently represent the standard calibrations for WR populations in external galaxies (Schaerer & Vacca 1998). Reduced optical line luminosities at lower metallicities *naturally* follow if the strength of WR winds depends upon metallicity, as recently proposed (Crowther et al. 2002; Vink & de Koter 2005), due to the combination of smaller line equivalent widths and lower optical continuum levels.

Wolf-Rayet stars with weak winds are capable of producing significant He II Lyman continuum photons (Schmutz et al. 1992; Smith et al. 2002), which we attribute to the origin of nebular He II $\lambda 4686$ in low metallicity galaxies. Application to IZw 18 suggests that WC stars are present in greater numbers than has been previously suggested, and that WN stars are extremely difficult to detect, since their winds appear to depend more sensitively upon metallicity than WC stars. An increased number of WR stars at low metallicity causes severe problems with evolutionary predictions for single stars.

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.

Acknowledgements. The majority of our NTT/EMMI observations were carried out in service mode, courtesy of John Pritchard, to whom we are grateful. We wish to thank Yuri Izotov for providing us with his MMT 2D spectrum of IZw 18 and Tony Moffat for a comprehensive referee's report which has helped to improve the original manuscript. Financial support was provided by the Royal Society (PAC) and PPARC (LJH).

References

- Barba, R. H., Niemela, V. S., Baume, G., & Vazquez, R. A. 1995, *ApJ*, 446, L23
- Bartzakos, P., Moffat, A. F. J., & Niemela, V. S. 2001, *MNRAS*, 324, 18
- Bouchet, P., Lequeux, J., Maurice, E., Prevot, L., & Prevot-Burnichon, M. L. 1985, *A&A*, 149, 330
- Breysacher, J. 1981, *A&AS*, 43, 203
- Breysacher, J., Azzopardi, M., & Testor, G. 1999, *A&AS*, 137, 117
- Brown, T. M., Heap, S. R., Hubeny, I., Lanz, T., & Lindler, D. 2002, *ApJ*, 579, L75
- Chandar, R., Leitherer, C., & Tremonti, C. A. 2004, *ApJ*, 604, 153
- Chen, H.-W., Prochaska, J. X., Bloom, J. S., & Thompson, I. B. 2005, *ApJ*, 634, L25

- Conti, P. S., & Morris, P. W. 1990, *AJ*, 99, 898
- Conti, P. S., Garmany, C. D., & Massey, P. 1989, *ApJ*, 341, 113
- Crowther, P. A. 2000, *A&A*, 356, 191
- Crowther, P. A. 2006, in *Proc. Stellar Evolution at Low Metallicity: Mass-Loss, Explosions, Cosmology*, ed. H. Lamers, N. Langer, & T. Nugis, ASP Conf Ser., in press [arXiv:astro-ph/0510063]
- Crowther, P. A., & Smith, L. J. 1997, *A&A*, 320, 500
- Crowther, P. A., & Dessart, L. 1998, *MNRAS*, 296, 622
- Crowther, P. A., Dessart, L., Hillier, D. J., Abbott, J. B., & Fullerton, A. W. 2002, *A&A*, 392, 653
- Crowther, P. A., Drissen, L., Abbott, J. B., Royer, P., & Smartt, S. J. 2003, *A&A*, 404, 483
- Crowther, P. A., Morris, P. W., & Smith, J. D. 2006, *ApJ*, 636, 1033
- de Mello, D. F., Schaerer, D., Heldmann, J., & Leitherer, C. 1998, *ApJ*, 507, 199
- Eldridge, J. J., Genet, F., Daigne, F., & Mochkovitch, R. 2005, *MNRAS*, submitted [arXiv:astro-ph/0509749]
- Foellmi, C., Moffat, A. F. J., & Guerrero, M. A. 2003a, *MNRAS*, 338, 360
- Foellmi, C., Moffat, A. F. J., & Guerrero, M. A. 2003b, *MNRAS*, 338, 1025
- Galama, T. J., et al. 1998, *Nature*, 395, 670
- Garnett, D. R. 1990, *ApJ*, 363, 142
- Gibson, B. K. 2000, *Mem. Soc. Astro. Ital.*, 71, 693
- Gräfener, G., Hamann, W.-R., Hillier, D. J., & Koesterke, L. 1988, *A&A*, 329, 190
- Gräfener, G., & Hamann, W.-R. 2005, *A&A*, 432, 633
- Heap, S. R., Ebbets, D., Malumuth, E. M., et al. 1994, *ApJ*, 435, L39
- Hilditch, R. W., Howarth, I. D., & Harries, T. J. 2005, *MNRAS*, 357, 304
- Hillier, D. J. 1989, *ApJ*, 347, 392
- Hillier, D. J. 1991, *A&A*, 247, 455
- Hillier, D. J., & Miller, D. L. 1998, *ApJ*, 496, 407
- Howarth, I. D. 1983, *MNRAS*, 203, 301
- Howarth, I. D., Murray, J., Mills, D., & Berry, D. S. 2003, *Starlink User Note 50.23*, Rutherford Appleton Laboratory
- Izotov, Y. I., & Thuan, T. X. 2004, *ApJ*, 616, 768
- Izotov, Y. I., Foltz, C. B., Green, R. F., Guseva, N. G., & Thuan, T. X. 1997, *ApJ*, 487, L37
- Kingsburgh, R. L., & Barlow, M. J. 1995, *A&A*, 295, 171
- Kingsburgh, R. L., Barlow, M. J., & Storey, P. J. 1995, *A&A*, 295, 75
- Koenigsberger, G., Georgiev, L., Barba, R., et al. 2000, *ApJ*, 542, 428
- Langer, N. 1989, *A&A*, 220, 135
- Li, Z.-Y., & Chevalier, R. A. 2003, *ApJ*, 589, L69
- Legrand, F., Kunth, D., Roy, J.-R., Mas-Hesse, J. M., & Walsh, J. R. 1997, *A&A*, 326, L17
- Lundström, I., & Stenholm, B. 1984, *A&AS*, 58, 527
- MacFadyen, A. I., & Woosley, S. E. 1999, *ApJ*, 524, 262
- Maeder, A., & Meynet, G. 1994, *A&A*, 287, 803
- Massey, P. 1984, *ApJ*, 281, 789
- Massey, P., & Johnson, O. 1998, *ApJ*, 505, 793
- Massey, P., & Duffy, A. S. 2001, *ApJ*, 550, 713
- Massey, P., Olsen, K. A. G., & Parker, J. Wm. 2003, *PASP*, 115, 1265
- Massey, P., Puls, J., Pauldrach, A. W. A., et al. 2005, *ApJ*, 627, 477
- Meynet, G., & Maeder, A. 2005, *A&A*, 429, 581
- Moffat, A. F. J., Marchenko, S. V., Bartzakos, P., et al. 1998, *ApJ*, 497, 896
- Mokiem, M. R., et al. 2006, *A&A*, submitted
- Morgan, D. H., & Good, A. R. 1985, *MNRAS*, 216, 459
- Morris, P. W., Crowther, P. A., & Houck, J. R. 2004, *ApJS*, 54, 413
- Pagel, B. E. J., Edmunds, M. G., & Smith, G. 1980, *MNRAS*, 193, 219
- Schaerer, D., & Vacca, W. D. 1998, *ApJ*, 497, 618
- Schaerer, D., Contini, T., & Pindao, M. 1999, *A&A*, 136, 35
- Schaerer, D., Guseva, N. G., Izotov, Y. I., & Thuan, T. X. 2000, *A&A*, 362, 53
- Schmutz, W., & Vacca, W. D. 1991, *A&A*, 248, 678
- Schmutz, W., Leitherer, C., & Gruenewald, R. 1992, *PASP*, 104, 1164
- Seaton, M. J. 1979, *MNRAS*, 187, P73
- Shapley, A. E., Steidel, C. S., Pettini, M., & Adelberger, K. L. 2003, *ApJ*, 588, 65
- Smith, L. F. 1968, *MNRAS*, 140, 409
- Smith, L. F., Shara, M. M., & Moffat, A. F. J. 1990a, *ApJ*, 348, 471
- Smith, L. F., Shara, M. M., & Moffat, A. F. J. 1990b, *ApJ*, 358, 229
- Smith, L. F., Shara, M. M., & Moffat, A. F. J. 1996, *MNRAS*, 281, 163
- Smith, L. J., Norris, R. P. F., & Crowther, P. A. 2002, *MNRAS*, 337, 1309
- Stanek, K. Z., Matheson, T., Garnavich, P. M., et al. 2003, *ApJ*, 591, 17
- Terlevich, E., Diaz, A. I., Terlevich, R., et al. 1996, *MNRAS*, 279, 1219
- Torres-Dodgen, A. V., & Massey, P. 1988, *AJ*, 96, 1076
- Udalski, A., Szymanski, M., Kubiak, M., et al. 1999, *Acta A*, 49, 201
- Vacca, W. D. 1992, Ph.D. Thesis, University of Colorado
- Vacca, W. D. 1994, *ApJ*, 421, 140
- Van Marle, A.-J., Langer, N., & Garcia-Segura, G. 2005, *A&A*, 444, 837
- Vink, J. S., & de Koter, A. 2005, *A&A*, 442, 587
- Vreeswijk, P. M., Ellison, S. L., Ledoux, C., et al. 2004, *A&A*, 419, 927
- Walborn, N. R., Drissen, L., Parker, J. Wm., et al. 1999, *AJ*, 118, 1684

Online Material

Table A.1. Photometric properties of single WNE stars in the LMC and SMC based upon our NTT/EMMI spectrophotometry, including He II $\lambda 4686$ line measurements. Interstellar extinction corrections follow a standard Seaton (1979) reddening law. Distances of 49 kpc and 62 kpc are adopted for the LMC and SMC, respectively (see text). We compare synthetic magnitudes with Torres-Dodgen & Massey (1988, TM88) and reddenings with Schmutz & Vacca (1991, SV91) and Massey & Duffy (2001, MD01). Two entries are listed for SMC WR11, providing photometry for the composite WN+? system and the observed He II $\lambda 4686$ flux, plus approximate photometry for the WN star, for which the resulting reddening has been used to obtain the He II $\lambda 4686$ line luminosity.

Star		Sp	v	$b-v$	$v-r$	Δv	$\Delta(b-v)$	$FWHM$	W_λ	F_{4686}	E_{B-V}	E_{B-V}	L_{4686}
BAT99	Br	Type	mag	mag	mag	- TM88 -		Å	Å	erg s ⁻¹ cm ⁻²	SV91	This work	erg s ⁻¹
1	1	WN3b	15.75	0.01	-0.03	-0.17	0.00	33	255	6.5×10^{-13}	0.16	0.29	5.2×10^{35}
3	3	WN4b	14.63	0.01	-0.08	-0.20	0.03	33	236	1.7×10^{-12}	0.11	0.29	1.3×10^{36}
5	4	WN2b	16.67	0.06	0.02	-0.21	-0.01	37	180	1.9×10^{-13}	0.37	0.37	2.0×10^{35}
7	6	WN4b	13.81	-0.10	-0.09	-0.06	-0.04	60	481	7.7×10^{-12}	0.26	0.13	3.5×10^{36}
15	12	WN4b	14.39	-0.03	-0.05	-0.22	0.04	35	312	3.0×10^{-12}	0.25	0.22	1.8×10^{36}
17	14	WN4o	14.16	-0.11	-0.15	-0.21	0.03	30	140	1.7×10^{-12}	0.06	0.20	9.7×10^{35}
18	15	WN3(h)	14.60	-0.17	-0.19	-0.12	-0.01	30	123	1.0×10^{-12}	0.09	0.14	4.7×10^{35}
23	-	WN3(h)	16.98	0.31	0.16	-	-	30	93	6.4×10^{-14}	-	0.78	2.9×10^{35}
24	19	WN4b	14.52	-0.04	-0.06	-0.07	-0.05	41	375	3.1×10^{-12}	0.02	0.19	1.7×10^{36}
25	19a	WN4ha	15.10	-0.23	-0.23	-	-	28	40	2.0×10^{-13}	-	0.08	7.4×10^{34}
26	20	WN4b	14.69	-0.05	-0.09	0.17	-0.22	30	236	1.7×10^{-12}	0.20	0.21	9.9×10^{35}
31	25	WN4b	15.39	0.03	-0.07	-0.17	-0.02	33	223	8.2×10^{-13}	0.16	0.33	7.5×10^{35}
35	27	WN3(h)	14.84	-0.14	-0.18	0.01	-0.14	30	172	1.1×10^{-12}	0.02	0.12	4.8×10^{35}
37	30	WN3o	16.43	0.21	0.07	-0.87	-	32	187	2.4×10^{-13}	-	0.58	35.2×10^{35}
40	33	WN4(h)a	14.70	-0.20	-0.17	-0.08	-0.03	27	61	4.6×10^{-13}	0.12	0.11	1.9×10^{35}
41	35	WN4b	14.88	-0.06	-0.05	0.05	-0.04	27	248	1.5×10^{-12}	0.01	0.20	8.7×10^{35}
46	38	WN4o	15.27	-0.05	-0.05	-0.14	-0.10	28	131	5.4×10^{-13}	0.26	0.26	3.8×10^{35}
47	39	WN3b	15.35	-0.10	-0.07	-	-	27	252	1.0×10^{-12}	-	0.15	4.8×10^{35}
48	40	WN4b	14.69	-0.09	-0.07	-0.21	-0.06	32	240	1.8×10^{-12}	0.06	0.17	9.3×10^{35}
50	41	(b) WN5h	14.49	-0.22	-0.18	-	-	21	32	2.9×10^{-13}	-	0.10	1.2×10^{35}
51	42	WN3b	15.19	-0.15	-0.18	-0.25	0.09	46	265	1.2×10^{-12}	0.00	0.09	4.8×10^{35}
56	46	WN4b	14.53	-0.10	-0.09	-0.15	-0.02	29	193	1.6×10^{-12}	0.05	0.23	1.0×10^{36}
57	45	WN4b	14.87	-0.09	-0.08	-0.20	-0.14	29	262	1.6×10^{-12}	0.12	0.21	9.5×10^{35}
60	49	WN4(h)a	14.29	-0.21	-0.23	-	-	30	39	4.2×10^{-13}	-	0.14	2.0×10^{35}
62	51	WN3(h)	15.14	-0.18	-0.16	-0.15	-0.03	30	121	5.8×10^{-13}	0.04	0.17	3.0×10^{35}
63	52	WN4ha:	14.58	-0.22	-0.22	-0.12	0.05	30	65	5.5×10^{-13}	0.09	0.11	2.3×10^{35}
65	55	WN4o	15.51	0.14	0.08	-	-	29	162	4.8×10^{-13}	-	0.54	9.1×10^{35}
66	54	WN3(h)	15.30	-0.19	-0.17	0.02	-	32	77	3.3×10^{-13}	-	0.12	1.4×10^{35}
67	56	WN5ha	13.74	-0.02	-0.06	0.01	-0.06	27	40	6.6×10^{-13}	0.36	0.34	6.2×10^{35}
73	63	(b) WN5ha	14.65	-0.16	-0.16	-	-	22	28	2.1×10^{-13}	-	0.18	1.1×10^{35}
74	63a	WN3(h)a	15.50	-0.14	-0.14	-	-	36	45	1.5×10^{-13}	-	0.19	8.5×10^{34}
75	59	WN4o	14.47	-0.11	-0.16	-	-	29	185	1.7×10^{-12}	-	0.17	8.8×10^{35}
81	65a	WN5h	15.38	0.00	-0.13	-	-	19	37	1.4×10^{-13}	-	0.37	1.4×10^{35}
82	66	WN3b	15.93	0.13	0.10	-0.37	0.16	32	243	5.0×10^{-13}	0.16	0.43	6.5×10^{35}
88	70a	(a) WN4b/WCE	17.75	0.46	0.42	-	-	45	325	1.1×10^{-13}	-	0.81	5.3×10^{35}
94	85	(a) WN4b	14.89	0.09	0.09	-0.12	-0.09	53	380	2.0×10^{-12}	0.25	0.35	2.0×10^{36}
117	88	(a) WN5ha	12.95	-0.16	-0.13	-0.06	-0.06	33	42	1.5×10^{-12}	0.16	0.17	8.0×10^{35}
122	92	WN5(h)	12.75	0.03	0.05	-0.25	-0.02	22	82	3.1×10^{-12}	0.43	0.44	4.2×10^{36}
128	96	WN3b	15.46	0.00	-0.07	0.76	0.09	30	317	1.0×10^{-12}	-	0.26	7.2×10^{35}
131	98	WN4b	14.27	-0.07	-0.14	-	-	27	220	2.3×10^{-12}	-	0.20	1.3×10^{36}
132	99	WN4b(h)	14.62	0.10	0.00	-0.29	0.03	31	301	2.1×10^{-12}	0.27	0.38	2.2×10^{36}
134	100	WN4b	14.51	-0.05	-0.20	-0.10	-0.04	34	267	2.4×10^{-12}	0.11	0.11	1.0×10^{36}
WR						Δb					MD01		
1		WN3ha	15.27	-0.10	-0.17	0.11		27	31.2	1.0×10^{-13}	0.28	0.26	1.1×10^{35}
2		WN5ha	14.39	-0.19	-0.26	0.16		18	15.9	1.2×10^{-13}	0.17	0.12	8.3×10^{34}
4		WN6h	13.48	-0.18	-0.21	0.08		20	43.8	9.7×10^{-13}	0.16	0.16	7.8×10^{35}
9		WN3ha	15.39	-0.25	-0.26			28	23.2	9.1×10^{-14}	0.19	0.07	5.4×10^{34}
10		WN3ha	16.05	-0.16	-0.24			30	24.7	4.0×10^{-14}	0.24:	0.17	3.3×10^{34}
11		WN4ha+?	15.17	-0.12	0.06			28	14.0	6.3×10^{-14}	0.50	0.47	
		WN4ha	15.70:	-0.14:	-0.14:			28	19.3			0.20:	5.8×10^{34}
12		WN3ha	16.17	-0.21	-0.21			28	22.1	4.1×10^{-14}	0.17	0.12	2.9×10^{34}

(a) Observations taken at airmass > 2 ; (b) Revised to WN5 from WN4 since N IV $\lambda 4058 \gg$ N V $\lambda \lambda 4603-20$ /N III $\lambda \lambda 4634-41$ (Smith et al. 1996).

Table A.2. Photometric properties of WC stars in the LMC based upon our Mt Stromlo 2.3 m/DBS spectrophotometry, including C IV $\lambda 5808$ line measurements. Interstellar extinction corrections follow a standard Seaton (1979) reddening law. A distance of 49 kpc and 62 kpc is adopted for the LMC (see text). We compare synthetic magnitudes with Torres-Dodgen & Massey (1988, TM88) and reddenings with Smith et al. (1990, S90). Spectral types are from Bartzakos et al. (2001).

Star		Sp	v	$b-v$	Δv	$\Delta(b-v)$	$FWHM$	W_λ	F_{5808}	E_{b-v}	E_{b-v}	L_{5808}
BAT99	Br	Type	mag	mag	– TM88 –		Å	Å	erg s ⁻¹ cm ⁻²	S90	This work	erg s ⁻¹
8	8	WC4	14.87	-0.05	-0.02	0.08	54	1317	5.3×10^{-12}	0.19	0.12	2.2×10^{36}
9	7	WC4	14.96	-0.11	-0.06	-0.01	55	1658	5.4×10^{-12}	0.25	0.13	2.4×10^{36}
10	9	(a) WC4+O9.5II	11.02	-0.28			62	74	7.8×10^{-12}		0.04	2.5×10^{36}
11	10	WC4	13.87	-0.08	-0.02	-0.02	73	1320	1.3×10^{-11}	0.20	0.09	4.8×10^{36}
20	16a	WC4+O	14.01	0.01			75	264	1.9×10^{-12}		0.33	1.6×10^{36}
28	22	WC4+O5-6V-III	12.05	-0.26	0.03	-0.07	67	183	7.7×10^{-12}		0.06	2.7×10^{36}
34	28	WC4+OB	12.76	-0.28	-0.13	-0.02	52	277	6.0×10^{-12}		0.04	1.9×10^{36}
38	31	WC4+O8I:	11.37	-0.26			70	96	7.5×10^{-12}		0.06	2.6×10^{36}
39	32	WC4+O6V-III	12.33	-0.27	-0.06	-0.04	75	215	6.3×10^{-12}		0.05	2.1×10^{36}
52	43	WC4	14.03	-0.11			61	1287	1.1×10^{-11}	0.07	0.09	4.4×10^{36}
53	44	WC4+OB	13.04	-0.19			72	525	8.3×10^{-12}		0.13	3.6×10^{36}
61	50	WC4	13.90	-0.06	-0.13	0.30	72	1218	1.4×10^{-11}	0.09	0.11	5.8×10^{36}
70	62	WC4+OB	13.93	0.11	-0.07	0.25	83	880	7.3×10^{-12}	0.30	0.39	7.4×10^{36}
84	68	WC4+OB	12.92	-0.17			63	411	7.9×10^{-12}		0.15	3.7×10^{36}
85	67	WC4+OB	12.04	0.00			72	100	4.4×10^{-12}		0.32	3.5×10^{36}
90	74	WC4	15.42	0.12	0.01	-0.07	57	1451	3.6×10^{-12}	0.39	0.28	2.6×10^{36}
121	90a	WC4	17.21	0.31			59	1258	7.4×10^{-13}		0.59	1.4×10^{36}

(a) Walborn et al. (1999) have published spatially resolved blue optical spectroscopy of the WC4 component (HD 32228-2) for which $b = 14.15$ mag.