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Wind properties of Wolf-Rayet stars at low metallicity: Sk 41 (SMC)*

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Abstract. The stellar properties of Sk 41 (AB4, WN5h), the only known single Wolf-Rayet star in the SMC, are derived from ultraviolet (IUE), optical (AAT) and near-IR (NTT) spectroscopy. Contrary to expectations for low metal environments, the stellar properties of Sk 41 are typical of equivalent WN stars in the Galaxy and LMC, with $T_*{\sim}$42kK, log($L/L_\odot$)=5.7, v_∞=1300 km s^{-1}, H/He$\sim$2 by number, and $\dot{M}/\sqrt{f}$=3$\times$10^{-5}$M_\odot$yr^{-1}, where f is the volume filling factor. The stellar luminosity of Sk 41 is 50% below the minimum value predicted by single star evolutionary models at the metallicity of the SMC, suggesting a deficiency in present evolutionary models at low metallicity.

Emission line luminosities of He II λ4686 and C IV $\lambda\lambda$5801-12 in SMC WR stars are not systematically lower than their Galactic and LMC counterparts. From 43 late-type and 59 early-type WN stars, log $L_\lambda^{\rm HeII}$= 36.0 erg s^{-1} and 35.8 erg s^{-1}, respectively, while log $L_\lambda^{\rm CIV}$=36.5 erg s^{-1}. from 25 early-type WC stars. This new calibration has application in deriving WR populations in young starburst galaxies.

Synthetic WN models are calculated *with identical parameters* except that metal abundances are varied. Following the Smith et al. WN classification scheme, CNO equilibrium models reveal that earlier spectral types are predicted at lower metallicity, i.e. WN3–4 at 0.04$Z_\odot$ versus WN6 at 1.0$Z_\odot$. This provides an explanation for the trend towards earlier WN spectral types at low metallicity.

Key words: stars: Wolf-Rayet – stars: fundamental parameters – stars: individual: Sk 41 – galaxies: Magellanic Clouds – galaxies: starburst

1. Introduction

Galaxies containing the youngest starbursts, with ages of a few Myr, are known as Wolf-Rayet galaxies (Vacca & Conti 1992) since they show the spectroscopic signature of large numbers of WR stars. At present, in excess of 140 WR galaxies have been discovered (Schaerer et al. 1999), including examples at very low metallicity, Z, such as I Zw18 with Z=0.02$Z_\odot$ (De Mello et al. 1998), probably typical of star forming galaxies in the early universe.

The O star content of starburst galaxies is derived from nebular Balmer line fluxes, while WR populations are obtained from comparing broad He II λ4686 and C IV $\lambda\lambda$5801-12 emission line fluxes with calibrations of individual Galactic and/or LMC WR stars (Schaerer & Vacca 1998).

Radiative driven wind theory predicts that $\dot{M} \propto Z^{0.5}$ (Kudritzki et al. 1989). Incorporating this effect into massive star evolutionary models implies that the minimum initial mass star reaching the WR phase through single star evolution is predicted to be a function of Z; 25$M_\odot$ in the Galaxy, 35$M_\odot$ in the LMC and 45$M_\odot$ in the SMC (Maeder 1997). Although WR winds are considered to be driven by radiation pressure, their mass-loss rates are assumed to be independent of metal content in current evolutionary calculations.

Do WR stars have comparable mass-loss properties and emission line strengths within various metallicity regions? Attempts to establish differences between the properties of O and WR stars in the Galaxy and LMC have proved inconclusive (e.g. Puls et al. 1996; Crowther & Smith 1997), since the metal content of the LMC differs from the Solar neighbourhood only by a factor of $\sim$2.

Consequently, the SMC represents our closest neighbour in which to establish whether the stellar properties of O and WR stars are affected by low metal content (12+log O/H=8.1; Russell & Dopita 1990). Walborn et al. (1995), Puls et al. (1996) and Prinja & Crowther (1998) demonstrated that SMC O-type stars indeed reveal lower mass-loss rates and slower winds, except amongst very early O giants and supergiants. Comparisons for Wolf-Rayet stars are more problematic, since they are very rare in the SMC, and almost entirely binaries (with the potential for an alternative evolutionary channel to single stars). Omitting O3 If/WN stars, the LMC contains 125 bona-fide WR stars (Breysacher et al. 1999), in contrast to only eight WR stars in the SMC, which are listed in Table 1. Crowther (1999) discusses the influence of metallicity dependent WR mass-loss rates on stellar spectra and ionizing flux distributions.

HD 5980 has recently received considerable interest because of a Luminous Blue Variable (LBV)-type eruption in one of its component stars (Barba et al. 1995; Koenigsberger et al. 1998;

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* Based, in part, on observations collected at the European Southern Observatory, La Silla, Chile (Proposal No. 61.D–0680 and 63.H–0683)

Table 1. Revised catalogue of SMC WR stars, updated from Azzopardi & Breysacher (AB, 1979) to include MDV1 (Morgan et al. 1991) and exclude the O3If/WN6 star AB2 (AzV39a, Walborn 1977). Spectral types follow Smith et al. (1996) for WN stars or Crowther et al. (1998) for the WO star. A foreground extinction of $E_{\rm B-V}$=0.03 mag is adopted, together with the SMC extinction law of Bouchet et al. (1985).

Name	AB	Sk	AzV	Sp Type	m_v sys	$E_{\rm B-V}$ mag	M_v sys	M_v WR
	1		2a	WN3+O4	15.2	0.26	-4.6	-3.6
	3		60a	WN4+O4	14.7	0.17	-4.8	-4.1
	4	41	81	WN5h	13.4	0.11	-5.8	-5.8
MVD1				WN3+O5:	15.6	0.10?	-3.7	-3.7
HD5980*	5	78	229	WN3–4+O7I	11.6	0.07	-7.5	-6.5
				WN11h	8.6	0.07	-10.5	-10.5
				WN6(h)	10.4	0.07	-8.7	-8.7
	6	108	332	WN3+O6.5I	12.1	0.07	-6.8	-5.2
	7		336a	WN3+O7	13.1	0.11	-6.2	-5.2
Sand 1	8	188		WO3+O4V	12.7	0.05	-6.1	-5.0

*: Three entries are given for HD 5980, correponding to circa 1981–84 (pre-outburst, Torres-Dodgen & Massey 1988), September 1994 (mid-outburst, Heydari-Malayeri et al. 1997), and December 1997 (post-outburst, own dataset).

Moffat et al. 1998), although its variability and multiplicity hinders the reliability of spectroscopic analysis.

In order to avoid uncertainties caused by binarity, a study of the only known single WR star in the SMC, Sk 41 (AB4), as discussed by Moffat (1988), is presented here, using the non-LTE line blanketed model atmosphere code of Hillier & Miller (1998). Its stellar properties are compared with counterparts in the Galaxy and LMC, and the role of metal content on spectral appearance is investigated. In addition, the line luminosities of He II λ4686 and C IV $\lambda\lambda$5801-12 in SMC WR stars are compared with Galactic and LMC WR stars, and a new calibration is derived.

2. Observations

UV, optical and near-IR spectroscopy of Sk 41 has been obtained from the International Ultraviolet Exporer (IUE) archive, the 3.9m Anglo-Australian Telescope (AAT) and the European Southern Observatory 3.5m New Technology Telescope (NTT), respectively. Following Smith et al. (1996), a spectral classification of WN5h is obtained for Sk 41, in comparison to previous classifications of WN6-A (Walborn 1986) or WN4.5 (Conti et al. 1989). Although it could be claimed that a WN5h+abs classification is more appropriate from the Smith et al. definition, we adopt WN5h because of the close similarity of Sk 41 with other WN5h stars, such as HD 65865 (WR10) and R136a1 (BAT99-108).

2.1. Optical spectroscopy

An optical spectrogram of Sk 41 was obtained at the AAT during 1992 November 3–6, using the RGO spectrograph, 25cm camera, Tektronix CCD (1024 × 1024, 24μm pixels), 1200V and 1200B gratings, plus a slit width of 2″. The measured spectral resolution in the extracted spectra is 1.6–1.8Å, using the FWHMs of the Cu-Ar arc spectra. Four settings covered 3670–6005Å, plus 6455–7263Å. A standard reduction was carried out as discussed by Crowther & Smith (1997). Subsequent analysis made use of DIPSO (Howarth et al. 1998). In addition, a low resolution flux calibrated spectrum of Sk 41 from Torres-Dodgen & Massey (1988) has been used.

2.2. Near-IR spectroscopy

Long slit, near-IR spectroscopy of Sk 41 was acquired with the NTT, using the Son OF Isaac (SOFI) instrument, a 1024×1024 pixel NICMOS detector, and low resolution IJ (GRB) and HK (GRR) gratings on 1 Sept 1999. The spectral coverage was 0.94–1.65μm and 1.50–2.54μm, respectively, with dispersions of 7.0Å/pix and 10.2Å/pix. The 0.6 arcsec slit provided a 2 pixel spectral resolution of 14–20Å. The total integration time was 960 sec at each grating setting. Atmospheric calibration was achieved by observing HD 10747 (B3V) immediately before or after Sk 41, at an close airmass (within 0.03). Similar observations of HD 2002 (F5V) permitted a relative flux correction, using a T=6,500K model atmosphere normalized to V=8.13 mag.

A standard extraction and wavelength calibration was carried out with IRAF, while FIGARO (Shortridge et al. 1999) and DIPSO were used for the atmospheric and flux calibration, first artificially removing stellar hydrogen features from the B3V spectrum. Convolving our fluxed spectra with suitable filters indicates J∼13.6, H∼13.5, and K∼13.3 mag.

2.3. UV spectroscopy

A short wavelength (SWP48325), high resolution (HIRES) *IUE* observation of Sk 41 was retrieved from the World Data Centre at the Rutherford Appleton Laboratory. This was obtained on 7 August 1993, with an exposure time of 20,340 sec and was reduced using IUEDR (Giddings et al. 1996). In addition, three final archive (IUEFA), low resolution, large aperture datasets were obtained from STScI. Two short wavelength (SWP6195, SWP107270) and one long wavelength (LWR5359) spectra were obtained between 15 Aug 1979 and 2 Dec 1980, with exposure times of 900, 1200 and 960 sec, respectively.

3. Spectroscopic analysis

The model calculations are based on the iterative technique of Hillier (1987, 1990) which solves the transfer equation in the co-moving frame subject to statistical and radiative equilibrium, assuming an expanding, spherically-symmetric, homogeneous and static atmosphere. Allowance is made for line blanketing and clumping following the formulation of Hillier & Miller (1998).

Calculations consider detailed model atoms of H I, He I-II, C IV, N III-V, O III-VI, Si IV and Fe IV-VII (see Dessart et al.

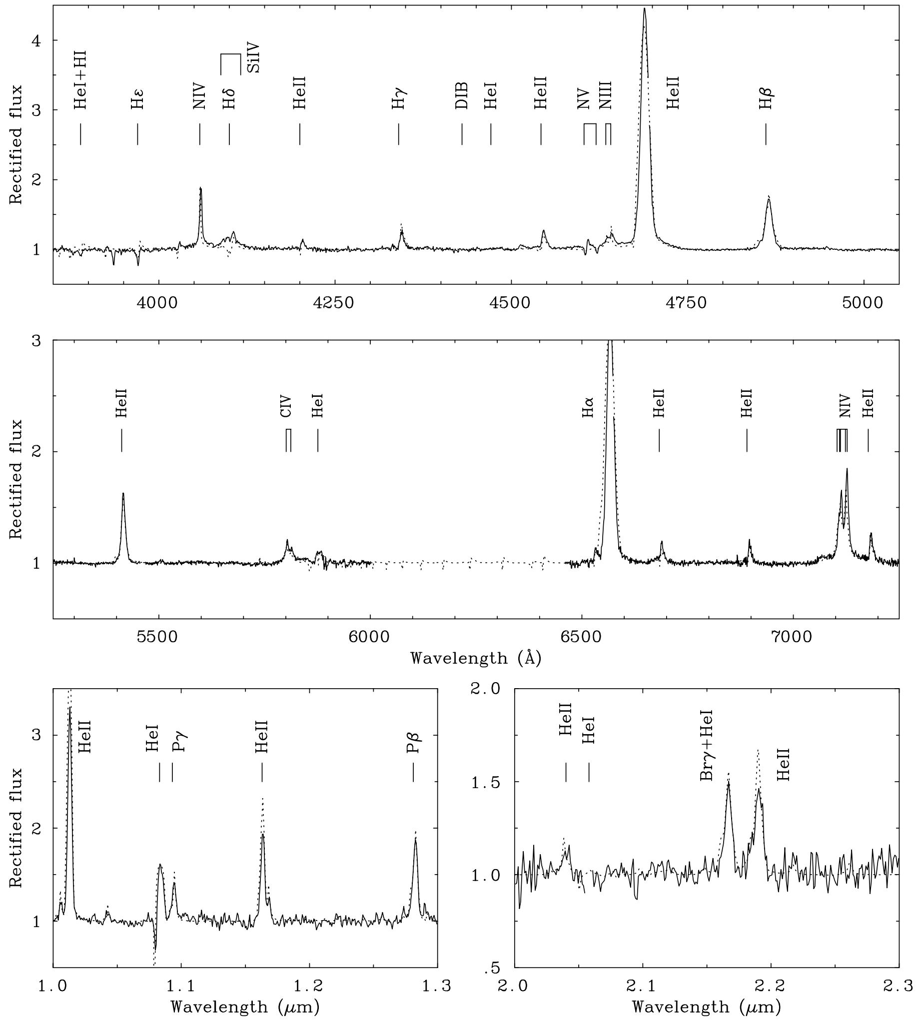

Fig. 1. Comparison between rectified optical (AAT/RGO) and near-IR (NTT/SOFI) spectroscopy of Sk 41 (solid) and synthetic spectra (dotted).

(2000) for details of the source of atomic data). Weak transitions of iron ($gf \leq 10^{-4}$) have been excluded without affecting the emergent spectrum. In total, 1027 full levels and 7680 non-LTE transitions are simultaneously considered. These are combined into 275 'super levels', with solely the populations of the super level calculated in the rate equations. Populations of individual atomic levels are then determined by assuming that it has the same departure coefficient as the super level to which it belongs.

In line with recent iron determinations for O stars in the SMC (Haser et al. 1998), abundances of elements other than hydrogen and helium are fixed at 0.2 × Solar (Si=0.02% by mass, Fe=0.03% by mass) or 0.2 × Solar CNO-equilibrium values (C=0.008%, N=0.3%, O=0.005% by mass).

The analysis technique follows that of Crowther et al. (1995), such that diagnostic lines of He I (λ10830), He II (λ5412) and H I (Hβ+He II λ4859) are chosen to derive the stellar temperature, mass-loss rate, luminosity and hydrogen content. The mass-loss rate is actually derived as the ratio $\dot{M}/\sqrt{f}$, where f is the volume filling factor. This can be constrained by fits to the electron scattering wings of the helium line profiles. A wind velocity of ∼1300 km s^{-1} is obtained from IUE/HIRES C IV $\lambda\lambda$1548-51 observations, although the S/N of this dataset is low. A standard β=1 velocity law is adopted, in order to provide consistency with recent analyses. However, recent evidence indicates that early WR winds accelerate more slowly (e.g. Lepine & Moffat 1999), so we have also investigated the effect of a slow β ∼10 law on derived stellar parameters. For Sk 41, a slow velocity law reveals a mass-loss rate that is systematically lower by ∼25%, with the stellar temperature and luminosity barely affected.

3.1. Stellar properties of Sk 41

Rectified optical (AAT/RGO) and near-IR (NTT/SOFI) spectroscopy of Sk 41 is compared with our synthetic spectra in Fig. 1. Overall, agreement is excellent for most H I, He I-II, N III-IV and C IV transitions. The fit to the He II λ4686 electron scattering wing is excellent using a clumped model with a volume filling factor of f=0.1. Note that N V $\lambda\lambda$4603–20 emission is not predicted, while the Hδ region, containing Si IV $\lambda\lambda$4088–4116 and N III $\lambda\lambda$4097–4103 is underestimated. Consistency between optical and near-IR fits in Sk 41 is good, although near-IR He II transitions, such as 1.01μm and 2.19μm, are ∼25% too strong, based on fits to optical He II transitions. Similar results

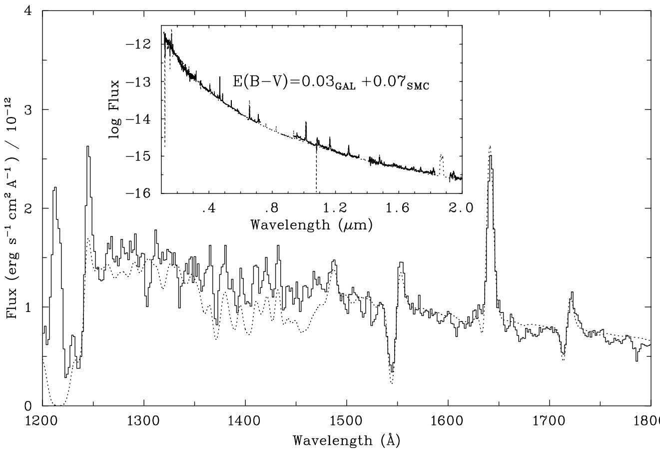

Fig. 2. Comparison between UV (IUE/LORES) spectrophotometry of Sk 41 (solid), dereddened by $E_{\rm B-V}$=0.03$_{\rm Gal}$ + 0.07$_{\rm SMC}$, with synthetic spectra degraded to the IUE resolution (dotted), allowing for interstellar Lyα absorption. The inset box compares the model energy distribution with UV-optical-IR observations.

were obtained for strong-lined WNE stars by Crowther & Smith (1996).

Fig. 2 compares the dereddened energy distribution of Sk 41 with model predictions, using a distance of 60.2 kpc to the SMC (Westerlund 1997). The Seaton (1979) extinction law is adopted for the foreground extinction, assumed to be E_{B-V}=0.03 mag. In addition, the Bouchet et al. (1985) SMC law as parameterised by Calzetti (priv. comm.) is used for internal SMC extinction. $E_{B-V} = 0.07$ mag is required to match the synthetic model (Fig. 2, inset box). SMC interstellar Lyman α absorption has been accounted for, assuming n(H I)=10$^{21.8}$ cm^{-2} (Fitzpatrick 1985).

Synthetic filter photometry from Torres-Dodgen & Massey (1988) indicates b=13.22 mag for Sk 41, so the absolute b-magnitude of Sk 41 is $M_b = -6.1$ mag. Agreement between the IUE dataset and the synthetic spectra (degraded to the IUE/LORES resolution) is reasonable, although imperfect in the $\lambda\lambda$1250–1500Å region, dominated by transitions of Fe V.

The derived stellar parameters for the WN5h star are T_*=42kK, R_*=13.6$R_\odot$, log($L/L_\odot$)=5.7, H/He=2.25 by number, and $\dot{M}/\sqrt{f}$=2.8×10$^{-5}M_\odot$yr^{-1}. The bolometric correction of this model is −3.9 mag, while the predicted number of ionizing photons shortward of H I λ911 and He I λ504 are log Q_0=49.45 s^{-1} and log Q_1=48.77 s^{-1}, respectively.

3.2. Comparison with WN stars in the Galaxy and LMC

Historically, WN5–6 spectral types have been considered solely as early WN (WNE) stars. In contrast, we assign a WNL status for those WN5–6 stars which contain atmospheric hydrogen following Smith et al. (1996), for consistency with evolutionary definitions. Consequently, the stellar properties of Sk 41 are shown in the upper panel of Fig. 3 (cross), together with a large sample of Galactic and LMC WN5–9 stars. Stellar parameters of the other stars are taken from Hamann et al. (1993, 1995),

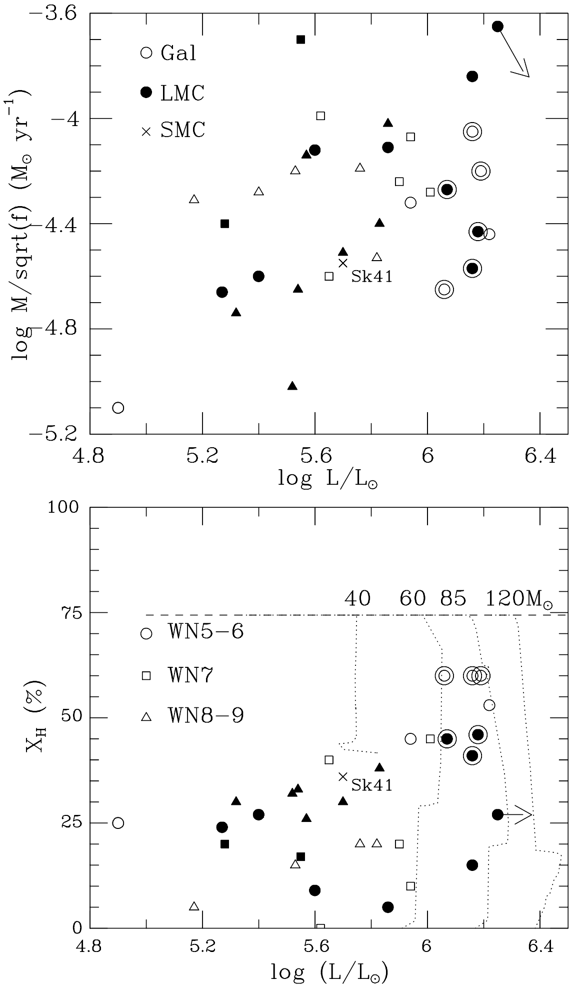

Fig. 3. Comparison between derived stellar properties of Sk 41 (WN5h, cross) with WNL stars at known distance in the Galaxy (open symbols) and LMC (filled symbols). Stellar parameters follow helium diagnostics, except for six members of giant H II regions, for which nitrogen diagnostics were adopted (concentric circles, Crowther & Dessart 1998). An arrow indicates the effect of using nitrogen instead of helium diagnostics for HD 38282 (BAT99-118, WN6h), although no shift is appropriate for Sk 41. Evolutionary predictions at 0.2$Z_\odot$ are shown as dotted lines (Meynet et al. 1994), with the main sequence (appropriate for the SMC) indicated by a dot-dashed line.

Crowther et al. (1995), Crowther & Smith (1997) and Crowther & Dessart (1998). Previous approaches were identical except that line blanketing and clumping were neglected, and nitrogen stellar diagnostics were employed by Crowther & Dessart (1998). The effect of selecting nitrogen, rather than helium diagnostics is indicated as an arrow for HD 38282 (BAT99-118, WN6h) in Fig. 3, although from the previous discussion no shift is appropriate for Sk 41.

The mass-loss rate of Sk 41 compares closely to other WNL stars with similar luminosities. A homogeneous model implies a wind performance number, $\dot{M}v_\infty/(L_*/c)$, of 3.6 for Sk 41, which compares closely with the three luminous WN5h stars in R136a (Crowther & Dessart 1998). Considering a volume filling factor of f=0.1 reduces the wind performance number for Sk 41 to approximately unity. Although the wind velocity of Sk 41 is a factor of two lower than that of the R136a stars, it is comparable to the sole Galactic WN5h star HD 65865 (WR10), for which v_∞=1500 km s^{-1} (Hamann et al. 1993).

It remains to be successfully demonstrated whether WR winds in high metallicity environments can be driven solely by multiple scattering (Schmutz 1997). Therefore, the wind properties of Sk 41 provide an excellent challenge at low metallicities.

3.3. Evolutionary model predictions at low metallicity

Since Sk 41 is apparently single, how do its properties compare with theoretical expectations for single massive stars at SMC metallicities (Meynet et al. 1994)? In the lower panel of Fig. 3 we show the luminosity and hydrogen content (in mass fraction) for a large sample of Galactic and LMC WNL stars, as well as Sk 41 (again indicated by cross). The latest evolutionary tracks for metallicities appropriate to the SMC (0.2$Z_\odot$, Meynet et al. 1994) are superimposed with initial masses of 40, 60, 85 and 120$M_\odot$. The minimum initial mass that is predicted to progress through to the WN phase has 45–50$M_\odot$, with log($L/L_\odot$) ~5.9, and a WN lifetime of ≤100,000 yr. Therefore, Sk 41 has a stellar luminosity which is 50% lower than the minimum that is predicted by evolutionary models. Since it is unlikely that Sk 41 is a disrupted binary (its radial velocity is typical of SMC stars), our results appear to identify a deficiency in present evolutionary models at low metallicity. Either less massive stars can advance to the WR stage, or the stellar luminosity decreases as the star reaches advanced evolutionary phases. These are completely determined by the mixing and the previous evolutionary phases, which remain poorly known.

4. Effect of metal content on spectral types of WN stars

If the mass-loss properties of WN stars in different environments are unaffected by metallicity, do differences in metal content have any effect on the emergent spectral appearance? To investigate this, we have *fixed* the stellar properties of Sk 41, and calculated additional models in which solely the metal content is varied by a factor of five, to solar (1.0$Z_\odot$) or 0.04$Z_\odot$, equivalent to twice the metal content of I Zw18, which is known to host WR stars (e.g. De Mello et al. 1998).

CNO elements are fixed at equilibrium WN values, appropriate for each environment (Meynet et al. 1994), such that the nitrogen content varies from 0.06% to 1.5% by mass. The atmospheric structures of these models are identical, except that since their outer wind temperatures are dependent on the cooling of the wind through metal resonance lines (Hillier 1988). At a radius of 10R_*, equivalent to $\tau_{\rm Ross}$ ~0.01, the wind temperature is $T_e^{\rm wind}$=23kK, 18.5kK and 16kK, for 0.04$Z_\odot$, 0.2$Z_\odot$ and 1.0$Z_\odot$, respectively.

Fig. 4 shows synthetic UV and optical WN spectra for each case. In the UV, differences between the models are dominated by the strength of Fe V-VI features and the appearance of N III $\lambda\lambda$1748–52 in the Solar metallicity model. Differences in blanketing play a minor role in the Lyman ionizing flux distribution

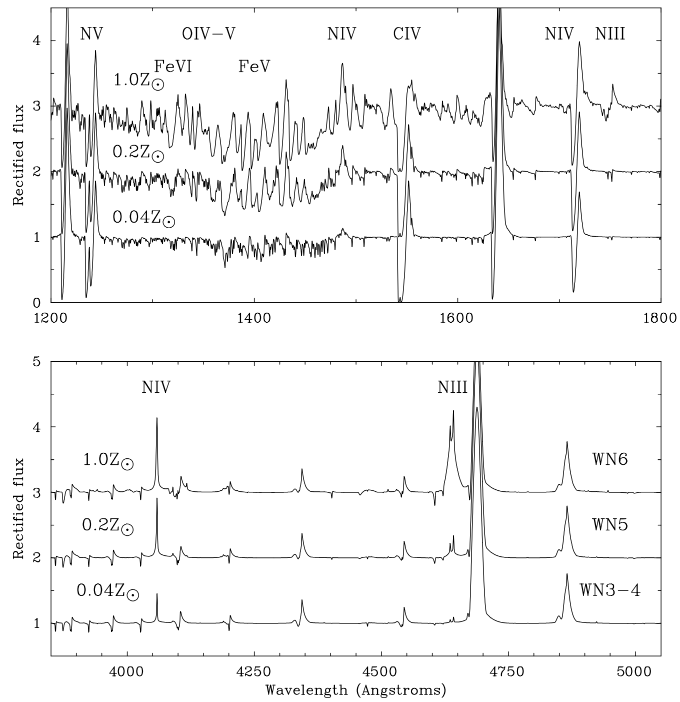

Fig. 4. Synthetic UV and optical spectra of WN models for which the metal content is varied between solar (1.0$Z_\odot$), SMC (0.2$Z_\odot$) and 0.04$Z_\odot$. In all cases assumed stellar parameters are T_*=42 kK, log($L/L_\odot$)=5.7, v_∞=1300 km s^{-1}, $\dot{M}$=9×10^{-6}$M_\odot$yr^{-1}, and f=0.1

of these models, although shortward of the O$^+$ edge (353Å) the higher blanketing of the 1.0$Z_\odot$ model predicts a factor of three times fewer ionizing photons than the 0.04$Z_\odot$ case.

From Fig. 4, the optical region reveals that solely low excitation lines, such as N III $\lambda\lambda$4634–41 and He I λ4471, are enhanced at high metallicities. He II λ4686 is essentially unaffected, as is N IV λ4058 due to its complex line formation mechanism, despite the factor of 25 decrease in nitrogen content. Differences for N III $\lambda\lambda$4634–41 are principally due to abundance effects. Lines formed in the outer wind, such as He I, are sensitive to wind cooling, such that the emission equivalent width of He I λ10830 decreases from 59Å at 1.0$Z_\odot$, to 35Å at 0.2$Z_\odot$ and 26Å at 0.04$Z_\odot$.

Therefore, although *identical* physical parameters are adopted in each WN model, *earlier* spectral types are obtained at *lower* metallicity. Following the scheme of Smith et al. (1996), whose spectral classification diagnostics were specifically chosen to avoid metallicity effects, the spectral type resulting from our sample of models ranges from WN6 at 1.0$Z_\odot$ to WN3–4 at 0.04$Z_\odot$ (the latter depending on the selection of diagnostic lines). This effect may contribute to the trend towards early WN types at low metallicities. Recall that 100% of SMC WN stars have spectral types of WN2–5, in contrast to 78% in the LMC and 46% in the Galaxy.

5. Line strengths of Wolf-Rayet stars

Unfortunately, definitive results are not possible from our comparison between the physical parameters of Sk 41 with the wide

Table 2. Comparison between mean line luminosities (in units of 10^{35} erg s^{-1}) and mean FWHM (Å) of He II λ4686 in Galactic, LMC and SMC WN stars, and C IV $\lambda\lambda$5801–12 in WC and WO stars. Note that we consider WN2–4 plus hydrogen-free WN5–6 stars as WNE stars, and WNL otherwise.

He II λ4686/	Galaxy				LMC				SMC				Total			
C IV λ5801	L_λ	σ	FWHM	N	L_λ	σ	FWHM	N	L_λ	σ	FWHM	N	L_λ	σ	FWHM	N
WNE†	7.6	5.0	33	18	5.8	5.6	28	37	2.7	0.8	25	4	6.1	5.4	29	59
WNL	7.6	6.5	17	17	13.5	14.2	16	25	7.8	–	13	1	11.0	11.9	16	43
WCE	17.0	10.5	47	9	40.3	18.1	64	16	–	–		0	31.9	19.4	58	25
WO*	2.6	–	150	1	15.8	–	103	1	32.3	–	92	1	14.9	11.1	104	4

†: HD 5980 has been excluded (see Sect. 5.2);
*: The WO total includes DR1 in IC1613 (Kingsburgh & Barlow 1995).

range of parameters observed in Galactic and LMC counterparts. Conti et al. (1989) have compared the emission equivalent widths of SMC WR stars with those of the Galaxy and LMC, which revealed that their emission lines are relatively weak. Massey et al. (1987) and Armandroff & Massey (1991) extended these comparisons to other Local Group galaxies. However, their conclusions are affected by binarity, or line-of-sight companions. Instead, absolute line luminosities are presented here, since they are unaffected by a binary companion, and also used to determine the WR stellar content of starburst galaxies. Comparisons with absolute visual magnitudes provide a superior indication of wind emission strengths. Conti & Massey (1989) provide a comparison between line fluxes and absolute visual magnitudes for LMC and Galactic WN stars, while Massey & Johnson (1998) present a similar comparison for LMC, SMC and M33 WN stars.

5.1. Sample of Wolf-Rayet stars

He II λ4686 (for WN2–9) and C IV $\lambda\lambda$5801-12 (for WC4–6 and WO) line luminosities have been measured in a large sample of Galactic, LMC and SMC WR systems, restricting the former to stars of known distance, generally through cluster/association membership. These two lines were selected since they are amongst the strongest features in all spectral types, and are commonly used to assess WR populations in starburst regions (Schaerer & Vacca 1998).

The majority of our measurements were taken from the Torres-Dodgen & Massey (1988) atlas, except where superior resolution fluxed datasets are available to us, obtained with either AAT/RGO, MSO 74inch/coude or MSO 2.3m/DBS during Dec 1991–Dec 1997 (e.g. Crowther & Smith 1997).

Absolute visual magnitudes have been calculated as follows. For WN stars, interstellar reddenings were generally obtained from weighted averages of Schmutz & Vacca (1991), Morris et al. (1993), Hamann et al. (1993), Hamann & Koesterke (1998) and our own determinations based on comparing dereddened optical and UV (IUE) datasets with theoretical WN flux distributions. Interstellar extinction laws follow Seaton (1979) for the Galaxy, Howarth (1983) for the LMC, and Bouchet et al. (1985) for the SMC. WC interstellar reddenings were weighted averages of Smith et al. (1990ab), Morris et al. (1993), Koesterke & Hamann (1995), Kingsburgh et al. (1995), Gräfener et al. (1998), and again our own determinations. Individual measurements are available upon request to the author. Spectral types are taken from Smith et al. (1990b, 1996) and Crowther et al. (1998). Magellanic Cloud distances are taken from Westerlund (1997), namely 51.2kpc and 60.2kpc for the LMC and SMC, respectively.

Absolute magnitudes of WR stars in binaries have been corrected for the presence of their OB companion. Where possible, previously estimated light ratios are adopted (e.g. Smith et al. 1996). Otherwise, standard OB calibrations are used. In some cases, such as AzV 2a (WN3+O4), O-type calibrations (Conti et al. 1983; Crowther & Dessart 1998) exceed the systemic absolute magnitude, so either the spectral type of their companions is in error, or they are sub-luminous. For these systems, we generally adopt $M_{\rm V}$(O)=$-$4.0 mag, with the exception of MDV1, for which no correction was applied (Table 1).

5.2. Line luminosities

In Figs. 5–6 we present line luminosities of Galactic, LMC and SMC WN and WC stars. Although the scatter is large, we confirm the trend towards higher line luminosities for WN stars with increasing M_v, previously identified by Conti & Massey (1989) for the LMC, and find a similar correlation for WCE stars. Absolute magnitudes of single stars (open symbols) are more reliable than members of binaries (filled-in symbols).

Table 2 presents mean line luminosities for Galactic, LMC and SMC WN and WC stars, and the combined sample. Note that the formal standard deviations are poor indicators, given the small numbers involved and non-gaussian distribution. From the table, the line luminosities of WN stars in the SMC are apparently a factor of 2–3 times lower than their LMC and Galactic counterparts. However, line luminosities of SMC WNE stars do not do not fall systematically below Galactic or LMC WNE stars with comparable (low) absolute magnitudes as shown in Fig. 5. Similarly, Sk 41 has a luminosity that is within ~20% of mean Galactic and LMC values, if the remarkable WN5–6 stars in LMC and Galactic giant H II regions are excluded (e.g. Crowther & Dessart 1998).

HD 5980 is omitted from the SMC sample shown in Table 2, since its line luminosity is from multiple components, highly

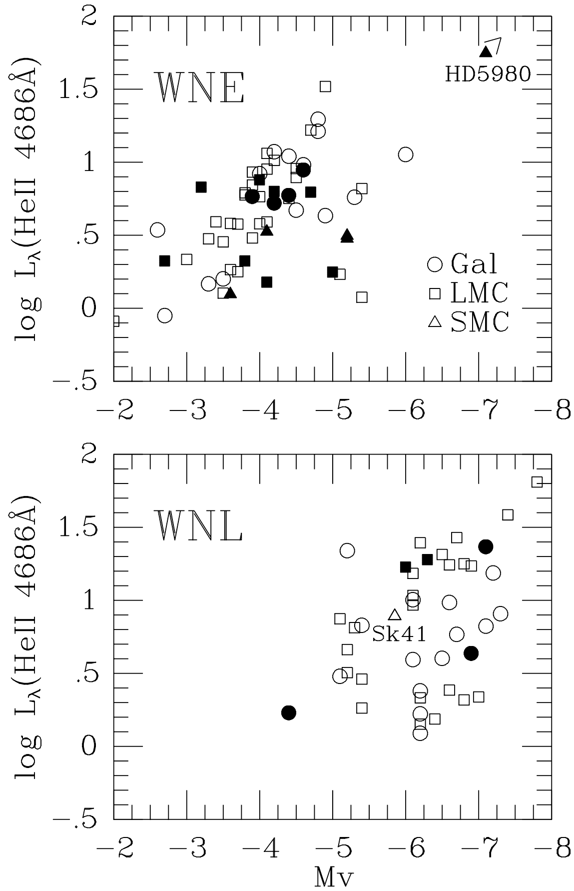

Fig. 5. Line luminosities (10^{35} erg s^{-1}) of He II λ4686 in WN stars. Galactic stars are represented by circles, LMC stars by squares and SMC stars by triangles. Single stars are open symbols, with binaries indicated by filled in symbols.

variable and indeed of uncertain origin[1]. The He II λ4686 luminosity of HD 5980 was 5.59×10^{36} erg s^{-1} in 1981–84, prior to outburst, when its spectral type was WN3–4. Observations obtained in Dec 1994, shortly after outburst, when the spectral type was WN8, revealed an even more remarkable He II line luminosity of 2.26×10^{37} erg s^{-1}, which is a factor of four greater than any other WN system from our sample, albeit with an equally impressive absolute visual magnitude (Table 1).

Amongst WC/WO stars, comparisons between the SMC and other galaxies are hindered by the absence of WC stars in the SMC. Amongst the WO stars with known distances, Sand 5 (WR142, WO2) in the Galaxy, Sand 2 (BAT99-123, WO3) in the LMC, and Sand 1 (AB8, WO3+O) in the SMC, it is Sand 1 which has the largest C IV λλ5801 luminosity. However, attempts to draw conclusions are severely hindered by the very low numbers involved. To illustrate this, DR1 (WO3) in the SMC-like IC 1613 has a C IV line luminosity which is a factor of three times lower than Sand 1 (Kingsburgh & Barlow 1995).

[1] Moffat et al. (1998) attribute pre-outburst line emission to material formed in the shocked region between two early type components, rather than a single WNE star

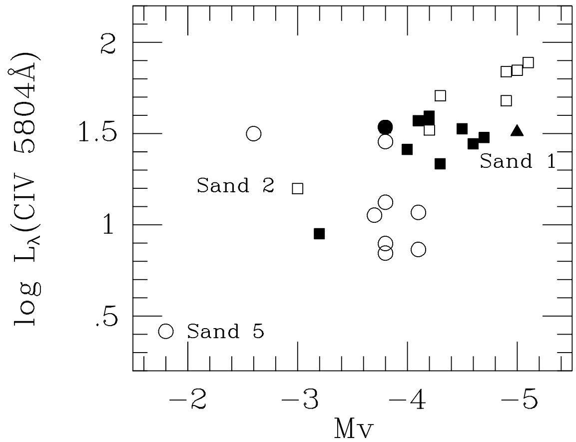

Fig. 6. Line luminosities (10^{35} erg s^{-1}) of C IV λλ5801-12 in WCE (WC4–6) and WO stars. Galactic stars are represented by circles, LMC stars by squares and SMC stars by triangles. Single stars are open symbols, with filled-in symbols for binaries. The identity of WO stars is shown.

Therefore, WO and WN stars in the SMC do not have systematically lower line luminosities than their higher metallicity counterparts. Therefore, mean values of our entire sample may be determined, and are indicated in Table 2. How do mean line luminosities compare with previous determinations? Smith et al. (1990a) obtained 3.3×10^{36} erg s^{-1} from observations of 5 LMC WC4 stars, which is confirmed here, based on a much larger sample of 25 Galactic and LMC WCE stars. More recently, Schaerer & Vacca (1998) obtained $(5.2\pm2.7)\times10^{35}$ erg s^{-1} from 26 WNE stars and $(1.6\pm1.5)\times10^{36}$ erg s^{-1} from 19 WNL stars. From 59 WNE stars, a 20% higher mean results here, while 43 WNL stars indicate a 30% lower calibration for late WN stars.

Note that application of these mean luminosities will lead to an overestimate of the true WN population in starburst regions by a factor of ∼2–3 if luminous WN5–6h stars dominate the WR signature, as is the case in 30 Dor and NGC 3603. Conversely, if the properties of constituent WNE stars are more typical of SMC stars, where close binary evolution probably plays an important role, the actual population would be underestimated by a similar factor.

5.3. *Line widths of Galactic, LMC and SMC WR stars*

If WR stars in the SMC have slower winds than their Galactic and LMC counterparts due to lower metallicity, we expect that their line widths will also be systematically lower.

However, in contrast to line fluxes, FWHM are sensitive to observational resolution. For example, AB7 has FWHM(He II λ 4686)=32Å from low resolution spectroscopy of Torres-Dodgen & Massey (1988), in contrast to 26Å from medium resolution AAT/RGO data. This observational limitation also complicates the Smith et al. classification scheme, which assigns 'b' for broad lined stars if FWHM(He II λ4686) ≥30Å (see also Conti 1999). Consequently, we have measured FWHM(He II) for a WR sample obtained with a uniform medium resolution of ∼2Å). Where these are unavailable, corrections to measurements from Torres-Dodgen & Massey (1988) datasets are made, using stars in common to both datasets as calibrators.

From Table 2, we find that the mean FWHM(He II λ4686) for WNE stars does decrease at lower metallicity, from 33Å in the Galaxy to 25Å in the SMC. However, since the SMC WR population is so low, taking into consideration the dependence of FWHM on individual spectral types, no unambiguous conclusions may be drawn. For example, LMC WCE stars reveal systematically higher FWHM (C IV λλ5801–12) than Galactic stars since the LMC WC population is solely represented by WC4 stars, which are rare in our Galaxy. The situation is further complicated in our Galaxy since Schild et al. (1990) and Armandroff & Massey (1991) identified a correlation between FWHM(C IV λλ5801–12) and galacto-centric distance for WCE stars in our Galaxy and M33, attributed to a metallicity gradient. Amongst WO stars, we find an apparent trend towards narrower lines at lower metallicity, again based on a very small sample.

6. Conclusions

Contrary to expectations, it appears that both the stellar properties and line luminosities of Wolf-Rayet stars in the SMC do not differ significantly from their counterparts in higher metallicity galaxies. Therefore, the reliability of studies of WR starburst galaxies at low metallicity based on template Galactic or LMC stars is supported here. However, individual spectral types may differ by up to a factor of ∼5 from mean WN, WC or WO line luminosity calibrations. Therefore, the question of what Wolf-Rayet flavours are produced in different star forming regions becomes relevant.

One added complication is that close binary evolution probably plays a major role in the formation of SMC WR stars, which may affect their physical properties. This is probably not the case for regions undergoing powerful bursts of massive star formation. It would be very useful to compare stellar properties and line luminosities of individual WR stars in low metallicity starbursts with the present calibrations, for which IC10 represents an ideal candidate (Massey & Armandroff 1995).

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