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Quantitative classification of WC and WO stars

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ABSTRACT

We present a quantitative classification scheme for carbon and oxygen sequence Wolf–Rayet stars. Our scheme uses new high-quality optical AAT and INT observations of 20 stars for which we provide narrow-band photometry and estimates of interstellar reddenings. In increasing order of excitation, our spectral classes range from WC11 to WC4 for Wolf–Rayet stars with a dominant carbon line visual spectrum, and subsequently from WO4 to WO1 for those with predominantly oxygen lines. We refine existing WC and WO schemes to incorporate stars with higher and lower excitation spectral features. Both massive stars and central stars of planetary nebulae (CSPNe) can be classified with the unified system. We have found no criterion that cleanly separates spectra of the two types of star, including elemental abundances (C/O or C/He). However, CSPNe show a wider range of line strength and width than massive stars in the same ionization subclass. Systematically lower FWHM(C IV λ5808) values are observed from WO-type CSPNe than from massive WO stars.

For WC4–11 stars, our primary diagnostic is the equivalent width or line flux ratio C IV λλ5801–12/C III λ5696. We extend the use of this as the principal criterion throughout the WC sequence, with few reclassifications necessary relative to Smith, Shara & Moffat. For WO stars, C III is absent and our new criteria, using primarily oxygen lines, take over smoothly. We define subclasses WO4–1, using O VI λλ3811–34/O V λ5590 as our primary diagnostic. The continuation in spectral sequence from WC to WO is used to indicate that the sequence is a result primarily of excitation effects, rather than significant abundance differences.

Our scheme allows us to confirm that massive stars and CSPNe are differently distributed over the subclasses. Around 3/5 of massive WC stars lie within the range WC5–8, while ≤1/5 of CSPNe are found within these spectral types. Stars within both the highest (WO1) and lowest (WC10–11) excitation spectral classes are unique to CSPNe. A WC classification for the hot R CrB star V348 Sgr is excluded (previously [WC12]) since both C III λ5696 and C IV λ5808 are absent in its optical spectrum. Additional criteria allow us to distinguish between WC-type, 'weak emission line' CSPNe, and O stars, allowing us to reclassify the central star of IRAS 21282+5050 (previously [WC11]) as an O star.

Key words: stars: fundamental parameters – stars: Wolf–Rayet – planetary nebulae: general.

1 INTRODUCTION

Until very recently, the spectral classification of Wolf–Rayet (WR) stars was based on a system developed for photographic plates. It was highly subjective to an individual observer and so was limited in its usefulness. The advent of linear digital detectors has facilitated the easy quantification of the WR classification system, allowing objective spectral classifications for WN2–8 stars (Smith, Shara & Moffat 1996), WN9–11 stars (Smith, Crowther & Prinja 1994), WC4–9 stars (Smith, Shara & Moffat 1990, hereafter SSM) and WO1–5 stars (Kingsburgh, Barlow & Storey 1995, hereafter KBS).

For WC-type central stars of planetary nebulae (CSPNe), qualitative schemes (e.g. Heap 1982; Méndez & Niemela 1982, hereafter MN) are still generally followed. This can lead to different classifications for very similar spectra. For example, Acker, Gorny & Cuisinier (1996) classified the CSPN M1–25 as a [WC6] star,[1] following MN. This object would be classified [WC5] according to the scheme of SSM. In addition, stars showing a late WC (WCL) appearance, first identified as a class by Webster & Glass (1974), have remained poorly distinguished despite efforts by Hu & Bibo (1990). Beyond the WC9 subclass, all WC-type stars known are CSPNe. It is important to develop and utilize *consistent* classification criteria for both CSPNe and massive WC stars in

[1]The [WC] notation follows van der Hucht et al. (1981) to distinguish CSPNe from classical WC stars, which for ease we shall refer to as massive (or Population I) objects.

Table 1. Log of observations for programme WC and WO stars, including narrow-band *ubvr* photometry (following Smith 1968b). Spectral classifications are taken from SSM for massive WC stars and Tylenda, Acker & Stenholm (1993) or Acker et al. (1996) for CSPNe, except for SwSt1, IRAS 17514−1555 (Hu & Bibo 1990) and IRAS 21282+5050 (Cohen & Jones 1987). Sources for intrinsic colours are discussed in the text, with interstellar reddenings probably reliable to ±0.05 mag [$E(B-V) = 1.21E(b-v)$: Turner 1982].

Star	Alias	PN G	Prev.Sp. Type	Telescope/ Instrument	Epoch	Sp. Coverage (Resolution Å)	v mag	$(b-v)$ mag	E_{b-v} mag
HD 193949	NGC 6905	061.4−09.5	[WC3]	2.5m INT-IDS	Jul 96	3700–6800 (3.0)	14.58	−0.02	0.25
HD 210092	NGC 7026	089.0+00.3	[WC3–4]	2.5m INT-IDS	Jul 96	3700–6800 (3.0)	14.72	0.58	0.85
HD 11758	IC 1747	130.2+01.3	[WC4]	2.5m INT-IDS	Jul 96	3700–6800 (3.0)	15.63	0.44	0.71
HD 177656	NGC 6751	029.2−05.9	[WC4]	2.5m INT-IDS	Jul 96	3700–6800 (3.0)	14.56	0.40	0.67
HD 192103	WR135		WC8	2.5m INT-IDS	Sep 91	3800–7300 (2.5)	8.44	0.21	0.41
HD 826	NGC 40	120.0+09.8	[WC8]	2.5m INT-IDS	Jul 96	3700–6800 (1.5)	11.82	0.15	0.35
HD 164270	WR103		WC9	3.9m AAT-RGO	Nov 92	3700–7300 (1.7)	8.94	0.18	0.38
HDE 313643	WR106		WC9	2.5m INT-IDS	Jul 96	5200–6800 (3.0)	12.40	0.91	1.11
	LS15 (WR119)		WC9	2.5m INT-IDS	Jul 96	5200–6800 (3.0)	12.48	0.77	0.97
	MR90 (WR121)		WC9	2.5m INT-IDS	Jul 96	5200–6800 (3.0)	12.33	1.14	1.34
HD 184738	BD+30^{o}3639	064.7+05.0	[WC9]	2.5m INT-IDS	Jul 96	3700–6800 (1.5)	10.30	0.09	0.29
He 2−459		068.3−02.7	[WC9]	2.5m INT-IDS	Jul 96	3700–6800 (1.5)	17.26	1.30	1.50
He 2−99	LSS 3169	309.0−04.2	[WC9]	3.9m AAT-UCLES	May 93	4050–5300 (0.2)	13.33	0.09	0.29
HD 167362	SwSt1	001.5−06.7	[WC10]	3.9m AAT-UCLES	May 93	3400–9900 (0.2)	11.77	0.22	0.51
	IRAS 17514−1555	012.2+04.9	[WC11]	2.5m INT-IDS	Jul 96	3700–6800 (1.5)	16.03	0.76	1.05
	M4−18	146.7+07.6	[WC11]	2.5m INT-IDS	Jul 96	3700–6800 (1.5)	14.14	0.02	0.31
He 2−113	He 3−1044	321.0+03.9	[WC11]	3.9m AAT-UCLES	May 93	3400–9900 (0.2)	11.93	0.55	0.84
	K2−16	352.9+11.4	[WC11]	2.5m INT-IDS	Jul 96	3700–6800 (1.5)	12.89	0.26	0.55
He 3−1333	CPD−56^{o} 8032	332.9−09.9	[WC11]	3.9m AAT-UCLES	May 93	3400–9900 (0.2)	10.87	0.27	0.56
	IRAS 21282+5050		[WC11]	2.5m INT-IDS	Jul 96	3700–6800 (1.5)	14.38	1.32	1.59

order to understand and test the apparent absence of WC5–7 stars amongst CSPNe.

In Section 2, we present new high-quality observations of several WC stars, including both CSPNe and massive stars. In Section 3, we present a new quantitative classification scheme for WCL stars that forms a natural extension to the existing scheme of SSM, and that applies equally to CSPNe and to massive stars. In Section 4, we consider whether early WC (WCE) or WO spectral classifications are more appropriate for higher ionization CSPNe and massive stars. Section 5 provides a brief summary.

2 OBSERVATIONS AND DATA REDUCTION

New observations of 15 (early and late) WC CSPNe and five Population I WCL stars were obtained from the 2.5-m Isaac Newton Telescope (INT), La Palma, Spain, and the 3.9-m Anglo-Australian Telescope (AAT), Australia. A log of our observations, together with a cross-index to alternative catalogue names, is given in Table 1.

There are some quantitative spectroscopic data for CSPNe available in the literature. Seven WCL stars have been observed by Leuenhagen, Hamann & Jeffery (1996). Two WCE CSPNe have been studied by Koesterke & Hamann (1997), while Wolf-Rainer Hamann has kindly provided us with observations of four high-excitation CSPNe (NGC 1501, 5189, 5315 and PB6), two of which were previously presented in Hamann (1996). We will also use spectroscopy of the CSPNe Sand 3 observed by Barlow, Blades & Hummer (1980), and include our previously unpublished red spectroscopy of He 2-99 obtained with the AAT–RGO spectrograph.

For massive WC4–WC9 stars, quantitative visual spectroscopy is available from Torres & Massey (1987) and SSM. The hot R CrB star V348 Sagittarii, which has in the past been classified WC12, has been observed by Leuenhagen, Heber & Jeffery (1994).

2.1 New optical spectroscopy

Our principal INT data set was obtained with the Intermediate Dispersion Spectrograph with the 235-mm camera, and a 1024×1024 Tektronix CCD. For most stars, complete spectral coverage between λλ3700 and 6800 at a two-pixel spectral resolution of 1.5 Å using 1200 line mm^{-1} gratings was obtained with four overlapping settings. For some broad-line stars, 3.0-Å resolution sufficed and only two settings were needed. A standard data reduction within IRAF (V2.10) was carried out, including bias subtraction, flat-fielding, sky subtraction and object extraction. Wavelength calibration was achieved by taking CuAr or CuNe exposures either before or after every stellar frame. Absolute flux calibration was obtained by taking wide-slit (5–10 arcsec, depending on conditions) exposures of targets and Oke (1990) flux standards (BD+33^{o} 2642, BD+28^{o} 4211). The continuum signal-to-noise ratio ranged from 80 to 100 in our extracted spectra. Subsequent analysis was also carried out within DIPSO (Howarth et al. 1995). Additional spectroscopy of HD 192103 (WR 135) was obtained with the INT-IDS, 500-mm camera and 400×590 pixel GEC CCD in 1991 September. 400 line mm^{-1} V and R gratings provided complete spectral coverage between λλ3800 and 7300 in seven overlapping wavelength settings (see Crowther, Hillier & Smith 1995 for details of the reduction process).

The majority of our AAT observations were obtained in 1993 May using the UCL Echelle Spectrograph (UCLES), 31 line mm^{-1}, and a Tektronix CCD (1024×1024, 24-μm pixels). Up to five wavelength settings provided complete wavelength coverage at $R = 50\,000$ between λλ3500 and 9500 for CPD−56^{o} 8032, He 2–113 and SwSt1, and between λλ4040 and 5300 for He 2–99. For each star wide-slit absolute spectrophotometry was also obtained. The continuum signal-to-noise ratios ranged from 20 to 60 depending on exposure time and the brightness of the object. These data were reduced using IRAF and subsequently analysed within DIPSO.

Table 2. Emission-line equivalent widths, W_λ (in Å), and de-reddened line fluxes, I_λ (in 10^{-12} erg cm^{-2} s^{-1}), of various classification diagnostics, plus the FWHM C III λ5696 or C IV λλ5801–12 (in Å). Fluxes are uniformly dereddened using interstellar extinctions from Table 1. IRAS 21282+5050 is omitted since it is no longer classified as a WC star (see text).

Star	FWHM		O VI λ3818		C II λ4267		He II λ4686		O VI λ5290		O III-V λ5590		C III λ5696		C IV λ5808		He I λ5876	
	λ5696	λ5808	W_λ	I_λ	W_λ	I_λ	W_λ	I_λ	W_λ	I_λ	W_λ	I_λ	W_λ	I_λ	W_λ	I_λ	W_λ	I_λ
NGC 6905	–	36.5	349.0	20.5	–	–	99.0	2.3	31.0	0.4	6.5	0.04	–	–	87.0	0.8	–	–
NGC 7026	–	63.0	108.0	96.0	–	–	87.0	40.0	44.0	2.8	31.4	2.1	–	–	86.5	6.0	–	–
IC 1747	–	36.0	<30	<4.5	–	–	82.0	3.8	10.2	0.3	53.0	1.5	–	–	416.0	8.7	–	–
NGC 6751	–	52.0	46.0	15.0	–	–	270.0	28.0	31.5	1.4	112.0	5.2	–	–	2270	95.0	–	–
HD 192103	37.8	26.9	5.5	88.0	17.5	210.0	81.0	1190	6.5	34.8	12.3	71.7	189.0	1300	215.0	1450	49.0	310.0
NCG 40	28.0	21.7	5.4	3.4	14.0	6.6	54.0	23.0	–	–	18.3	3.4	140.0	29.0	164.0	32.0	25.0	4.6
He 2–459	34.9	29.4	–	–	25.0	5.4	50.0	9.4	–	–	17.2	1.2	244.0	26.0	99.5	9.6	41.0	3.4
He 2–99	16.6	15.6	–	–	23.7	4.1	26.7	23.0	–	–	20.0	1.5	245.0	18.0	96.0	5.8	41.0	3.2
HDE 313643	18.3	30.0	–	–	22.4	81.0	16.9	52.0	–	–	5.2	6.3	196.0	240	71.0	71.0	55.9	54.0
LS 15	16.7	32.6	–	–	19.5	46.0	11.2	27.0	–	–	4.4	3.5	192.0	120.0	62.0	30.0	46.0	21.0
HD 164270	18.0	30.0	–	–	24.8	160.0	13.8	100.0	–	–	4.6	15.5	235.0	690.0	69.0	170.0	56.5	155.0
MR 90	18.2	28.7	–	–	22.9	220.0	12.0	110.0	–	–	3.1	7.7	206.0	450.0	58.0	130.0	47.5	110.0
BD+30° 3639	14.1	–	–	–	15.6	25.0	11.3	18.0	–	–	4.0	3.0	172.0	120.0	39.0	25.0	27.5	15.0
SwSt1	5.4	–	–	–	1.5	1.2	2.9	2.1	–	–	0.5	0.2	32.9	12.0	6.3	2.2	3.4	1.1
IRAS 17514–1555	5.8	–	–	–	24.5	2.9	2.2	0.2	–	–	1.0	0.05	26.3	1.4	4.1	0.2	24.9	1.3
CPD–56°8032	4.0	–	–	–	24.5	61.0	1.4	2.4	–	–	1.0	0.8	17.9	15.0	2.4	2.1	22.6	17.0
M 4–18	3.5	–	–	–	11.4	0.64	1.0	0.03	–	–	0.3	0.01	14.4	0.33	0.9	0.02	11.3	0.03
He 2–113	2.9	–	–	–	9.6	31.0	0.6	1.5	–	–	0.3	0.3	14.5	18.0	1.5	1.6	9.6	11.0
K 2–16	3.3	–	–	–	4.1	2.0	<0.1	<0.01	–	–	<0.1	<0.01	3.6	0.57	<0.1	<0.01	3.3	0.51

Full details of the data reduction are provided by De Marco, Barlow & Storey (1997). Additional AAT observations of HD 164270 (WR 103) were obtained in 1992 November using the RGO Spectrograph, 250-mm camera, Tektronix CCD and 1200V grating, covering λλ3680–6000 in three overlapping settings (again see Crowther et al. 1995).

2.2 Photometry and emission-line strengths

In Table 1, we include narrow-band synthetic photometry (following Smith 1968b) obtained by convolving each of our flux-calibrated data sets with suitable Gaussian filters. Intrinsic colours for WC stars have been obtained from test non-LTE model atmosphere calculations. We find $(b-v)_0 \sim -0.27$ mag for WCE stars, $(b-v)_0 \sim -0.20$ mag for WC8–9 stars, $(b-v)_0 \sim -0.29$ mag for WC10–11 stars and $(b-v)_0 \sim -0.27$ mag for late O stars. From these intrinsic colours, estimates of interstellar (and/or circumstellar) reddenings can be made and are included in Table 1. Note that the colour excess for IRAS 21282+5050 is based on our reclassification to a late O star (Section 3.2). In many cases, our photometric magnitudes differ greatly from previously published values that were obtained from Johnson photometry or from direct images and that suffered from significant stellar and nebular contamination.

In Table 2, we present selected emission-line equivalent widths (W_λ) and dereddened fluxes (I_λ) that will be used as classification criteria for WC stars. It is important to emphasize that all equivalent widths and fluxes used for our quantitative classification are *emission* measurements, with P Cygni absorption components neglected. In the case of the C IV λλ5801–12 doublet for WCL stars, we add emission components together when they are resolved (valid for all stars cooler than WC9). He II λ4686 is only well resolved from C III λ4650 in WC9 and later subtypes. It is likely that certain line measurements include contributions from other unidentified features, although these are (reasonably) anticipated to affect all stars in a similar manner. Nebular contributions to emission lines were removed through subtraction by Gaussian fits (using the ELF suite of programs within DIPSO). Although equivalent width measurements provide our principal diagnostic criteria, we have included line flux measurements in Table 2 since the stellar continuum may be significantly affected by the nebular continuum, especially for unresolved extragalactic PNe. Since this preferentially contaminates at longer wavelengths, line equivalent width ratios at different wavelengths will be differentially affected. All fluxes were dereddened using the colour excesses determined in Table 1 and the standard Galactic reddening law of Howarth (1983) assuming $R = 3.1$.

3 CLASSIFICATION OF WCL STARS

3.1 Previous WCL schemes

The current optical classification scheme for WC stars is based upon measurements of carbon and oxygen emission lines, namely C III λ5696, C IV λλ5801–12 and O III–V λ5590 (SSM). The carbon lines, together with the λ4650 blend, represent the strongest emission features in the visual spectra of WC stars, and are relatively well separated for all subtypes. (C IV λλ5801–12 suffers from some contamination from He I λ5876 for those stars showing the broadest line spectra). The oxygen feature is currently used principally to distinguish between WC4–6 stars (see Section 4), since it is weak at later spectral types.

Webster & Glass (1974) noted that the nuclei of CPD−56°8032, He 2-113, M 4-18 and V348 Sgr have spectra in which C II emission lines dominate those of C III, implying spectral types later than WC9, the latest that had been defined at that time for massive WC Wolf–Rayet stars (Smith 1968a). Carlson & Henize (1979), on the basis of data from Swings & Struve (1943), classified SwSt1 as WC10 and inferred still later spectral types for the four stars discussed by Webster & Glass (1974). van der Hucht et al. (1981) were the first to classify the four nuclei discussed by Webster & Glass (1974) as WC11 (their table IX).

To date, the only attempt at a more quantitative classification was made by Hu & Bibo (1990) for WC10–12 subtypes, based on C II–IV lines, including C II λλ5641–62. We were motivated to develop an improved scheme for WCL stars because of the apparently contradictory classification provided for CPD−56° 8032 by Hu & Bibo (1990). For this star, a WC11 classification was proposed, signifying no C IV λλ5801–12 emission, yet our spectra clearly show P Cygni emission for this doublet (see Section 3.2). Acker et al. (1996) have suggested that the scarcity of [WC10] CSPNe relates to the definitions from Hu & Bibo (1990) being poorly linked to earlier subclasses, and proposed renaming the [WC10] subclass [WC10–11].

3.2 New WCL classification scheme

We have adopted the C IV λλ5801–12/C III λ5696 ratio as our primary classification diagnostic since it is observed throughout the WC sequence, providing consistency with the scheme of SSM. In our scheme we require a minimum signal-to-noise ratio of ∼20, plus a spectral resolution of ≈5–10 Å for adequate classifications in general. Since late WC (WC10–11) stars have very small line widths, they require an improved spectral resolution of ≈2 Å.

O III–V λ5592/C III λ5696, the secondary criterion of SSM, suffers from variations in C/O abundances, and becomes a crude discriminator of spectral subclass for WCL stars because of the weakness of the O III λ5592 feature. We have therefore sought alternative secondary diagnostics, which are preferably strong, relatively unblended features from the same element in the yellow–red part of the spectrum. We find that C IV λλ5801–12/C II λ4267 and He II λ4686/He I λ5876 provide useful discriminators between WC8–11 subclasses. Although C II λ4267 is difficult to measure in stars suffering from high interstellar reddening, it remains superior to alternative C II diagnostics, such as C II λλ5640–62 proposed by Hu & Bibo (1990), which is extremely weak and consequently difficult to measure for stars of earlier subtype than WC10. Alternative C II features at longer wavelengths either are badly blended (C II λλ6578–82 with [N II] λ6583), or lie in a rarely observed part of the spectrum (C II λλ7231–7237). Although helium diagnostics are severely blended with carbon features in WCE stars (C III–IV λ4650 and C IV λλ5801–12), the narrower emission lines of WCL stars allow reliable He II λ4686 and He I λ5876 measurements to be made for most WCL stars in our sample (with the possible exception of He 2–459).

Fig. 1 plots our primary and secondary classification line ratios for WCL stars, including massive (open symbols) and CSPN (filled symbols) WC stars. Since our observational sample includes only a small fraction of known massive WC8–9 stars, we have included our own measurements of 16 other WC8–9 stars from the spectrophotometry of Torres & Massey (1987). Boundaries between subtypes are marked. Note the natural breaks between subclasses WC8–9, 10 and 11 in both line ratios and line strength. This remains unexplained.

Overall, our measurements support the classification criteria adopted by SSM, with the exception of the WC8–9 boundary. We have revised this from W_λ(C IV)/W_λ(C III)= 0.4 to a value of 0.5 as this appears to represent a more natural division. Following SSM, He 2–459 [with W_λ(C IV)/W_λ(C III)= 0.41] would be classified as a [WC8] star, while He 2–99 [with W_λ(C IV)/W_λ(C III)= 0.39] would be defined as a [WC9] star, despite showing a very similar spectral morphology. Our revised criteria yield [WC9] classifications for both stars. HD 117297 (WR53) is reclassified to WC9 from WC8 (SSM), since W_λ(C IV)/W_λ(C III)= 0.43.

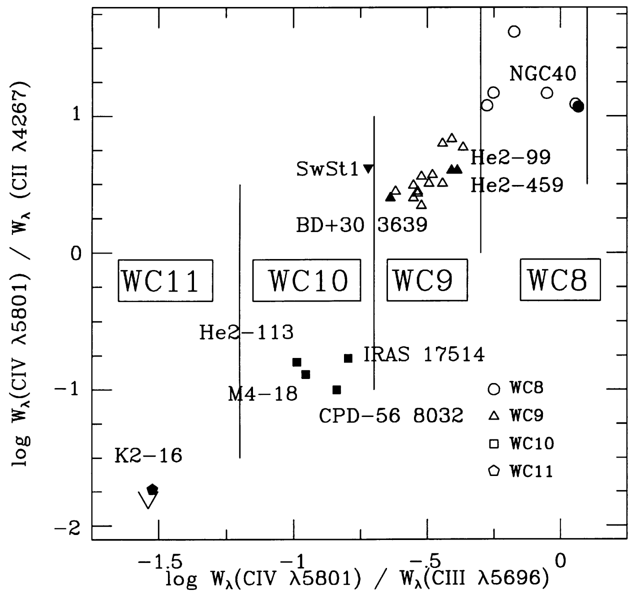

Figure 1. Emission-line equivalent width ratios for our principal and secondary criteria for WCL stars (filled: CSPNe, open: massive Population I) including measurements for massive WC8–9 stars from Torres & Massey (1987). The natural separation between subtypes is apparent, with divisions marked as solid lines. Similar relations are provided by line flux ratios listed in Table 1. SwSt1 (inverted triangle) is given a WC9 classification because of our secondary criterion (see text), while the arrow for K2–16 indicates that its position is an upper limit.

Fig. 1 confirms the conclusion of Méndez et al. (1991) that there is no clear distinction in line strength between massive WCL stars and WCL-type CSPNe, contrary to the early suggestion by Smith & Aller (1971). Nor is there any separation in line width. In our sample, CSPNe show both the broadest (He 2–459) and narrowest (BD+30° 3639) lines among WC9-type stars. Apart from the absence of massive WC stars with spectral type later than WC9, only the presence or absence of the nebula distinguishes between massive and CSPN WC stars (see also Lundström & Stenholm 1996).

Table 3 summarizes the primary (C IV/C III) and secondary (C IV/C II, He II/He I) classification criteria, with examples for each class. L302 in the SMC (Monk, Barlow & Clegg 1988) provides a useful test of our flux ratio criteria, since its continuum is heavily contaminated by its nebula. Both our primary and secondary flux ratio criteria support the previously derived WC8 classification for this star, with possible nebular He I contamination affecting the helium criterion.

While the classification scheme described above readily accommodates most stars, some remarks are necessary relating to particular objects showing unusual spectral characteristics.

SwSt1 (HD 167362) defies WC spectral classification in any of the proposed schemes. Both Smith & Aller (1969) and Méndez et al. (1991) suggested a composite Of–WR classification; Carlson & Henize (1979) and Hu & Bibo (1990) proposed a WC10 classification; and Tylenda et al. (1993) suggested that it was a 'weak emission line' wel star. The latter classification is certainly not appropriate for SwSt1 since very weak C III emission is expected for wel stars, yet W_λ(C III λ5696)= 33Å for SwSt1 – stronger than in all WC10–11 stars. Neither is an Of–WR classification appropriate since the criterion for an Of star (Conti 1976) is 'photospheric lines

Table 3. Quantification of WC11–4 and WO4–1 subclasses based on emission equivalent width ratios (W_λ) or dereddened line flux ratios (I_λ), providing a natural connection to SSM for most WC spectral types. To exclude O-type and weak emission line stars from WC or WO classifications, additional criteria include W_λ(C III λ5696)≥3 Å and either C II or C IV in emission for WCL stars, and W_λ(C IV λ5808)≥10 Å and either C III or O VI in emission for WCE or WO stars.

Subtype	FWHM (Å)	Primary	Secondary	Additional Criteria	Examples
	C III λ5696	C IV λ5808/C III λ5696	C IV λ5808/C II λ4267	He II λ4686/He I λ5876	
		log W_λ or log I_λ	log W_λ	log W_λ	
WC11	~3	≤ − 1.2	≤ − 1.5	He II λ4686 absent	K2–16
WC10	3–6	−1.2 to −0.7	−1.5 to −0.2	≤ − 0.8	CPD–56°8032
WC9	30±15	−0.7 to −0.3	−0.2 to +1.0	−0.8 to +0.1	He 2–99, HD 164270
WC8	40±10	−0.3 to +0.1	≥1.0	≥0.1	HD 192103, NGC40
	C IV λ5808	C IV λ5808/C III λ5696	C III λ5696/O III-V λ5590	O VI λ3818/C IV λ5808	
		log W_λ or log I_λ	log W_λ or log I_λ	log W_λ	
WC7	45±20	+0.1 to +0.6	≥0.1	≤ − 1.5	HD 156327
WC6	50±20	+0.6 to +1.1	+0.0 to +0.7	≤ − 1.5	HD 92806
WC5	50±20	+1.1 to +1.5	−0.4 to +0.5	≤ − 1.5	HD 165763, M1–25
WC4	70±20	≥1.5	≤ − 0.4	≤ − 1.5	HD 32257, NGC 5315
	C IV λ5808	O VI λ3818/O V λ5590	O VI λ3818/C IV λ5808	O VII λ5670/O V λ5590	
		log W_λ	log W_λ	log W_λ	
WO4	60±30	−0.3 to +0.25	−1.5 to −1	≪0.0	MS4, NGC1501
WO3	90±30	+0.25 to +0.6	−1 to +0.2	≪0.0	Sand 2, NGC7026
WO2	160±20	+0.6 to +1.1	≥ + 0.2	≤0.0	Sand 4
WO1	40±10	≥1.1	≥ + 0.2	≥0.0	NGC 6905

uncontaminated by wind emission in the visual spectrum', and Méndez et al. (1991) demonstrated that the usual O star classification (photospheric) absorption line at He II λ4542 is blueshifted, i.e. affected by wind emission. From Fig. 1, our primary classification criterion supports a WC10 subclass (as proposed by Carlson & Henize 1979), although it lies very close to the WC9 boundary. The line widths are more representative of WC10 than WC9. However, measurements based on alternative high-resolution spectroscopy indicate W_λ(C IV)/W_λ(C III)= 0.27, characteristic of a WC9 star, and stellar He I and C II signatures are very weak, i.e. *both* our secondary criteria indicate WC9. We suggest a WC9pec classification for this star.

K2–16 appears to have a significantly lower ionization than the other late-type CSPNe in Fig. 1, yet it was given the same classification by Tylenda et al. (1993). Our revised classification criteria make K2–16 the sole CSPN in the WC11 subclass. However, we note that W_λ(C III λ5696)/W_λ(C II λ4267) for this star (0.88) lies within the range observed for WC10 stars, namely 0.73–1.5. This implies that its difference from WC10 stars is a result of lower wind density rather than lower ionization. Strictly speaking, we should exclude a WR classification for K2–16, since photospheric features may be present in its spectrum (the spectral resolution of our observations is insufficient to verify any wind contamination of these features). An Of–WR(C) classification is inappropriate, because He II λ4686 is in absorption. An alternative could be to assign a peculiar O–WC10 classification. However, we feel that WC11 better indicates the close similarity to WC10 spectra and is more useful for our understanding of its nature.

Fig. 2 presents spectra of our programme WCL stars that cover our spectral diagnostics. They are ordered by new spectral subclass. For uniformity, spectra were rebinned to 1 Å per resolution element; strong features were rescaled so that weak features are still clear. As previously discussed, WC8–9 and WC10–11 stars are very distinct in their line strengths and ratios.

3.3 Can we distinguish between WCL-type stars and other emission-line stars?

C III λ5696 emission is not restricted to WC stars, and is observed in many other emission-line stars including late O stars (Crowther & Bohannan 1997), and wel CSPNe. Tylenda et al. (1993) defined wel stars as those with weak and narrow C IV λλ5801–12 emission, and with C III very weak or undetectable. In order to avoid confusion between WCL, O-type and wel for stars in which the stellar continuum is well defined, we shall impose two additional criteria necessary for a WCL-type classification, namely sufficient C III λ5696 emission (W_λ≥3 Å) plus emission (W_λ≥1 Å) at either C II λ4267 or C IV λλ5801–12. Obviously, these criteria do not apply to high-excitation WCE stars since C III λ5696 has negligible strength in WCE and WO stars (Section 4).

To illustrate the border region, we now discuss IRAS 21282+5050 which Cohen & Jones (1987) classified as a [WC11] star. This is a heavily reddened emission-line star [$E(B-V) = 1.92$ mag from Table 1] that has received little attention to date. Our observations cover a greater spectral range at a superior resolution than those of Cohen & Jones and reveal that W_λ(C III λ5696)= 2 Å, with neither C IV λλ5801–12 nor C II λ4267 observed in emission. Therefore this star fails both of our WCL criteria. It appears to be a peculiar O-type star, as shown in Fig. 3 where we compare its blue and yellow spectra with those of the O8 If star HD 151804 (Crowther & Bohannan 1997). In the yellow part of the spectrum, the similarities with the O supergiant are striking: specifically, the C III λ5696 emission and weak He I λ5876 P Cygni profile. However, in the blue, the spectra are quite different, with He II λ4686 in *emission* in HD 151804 and in *absorption* in IRAS 21282+5050, and with strong C III λλ4647–51 absorption in the latter, possibly as a result of chemical peculiarities. From comparison with spectral standards from Walborn & Fitzpatrick (1990) we propose an O9–9.5 classification for IRAS 21282+5050 based on the observed He II

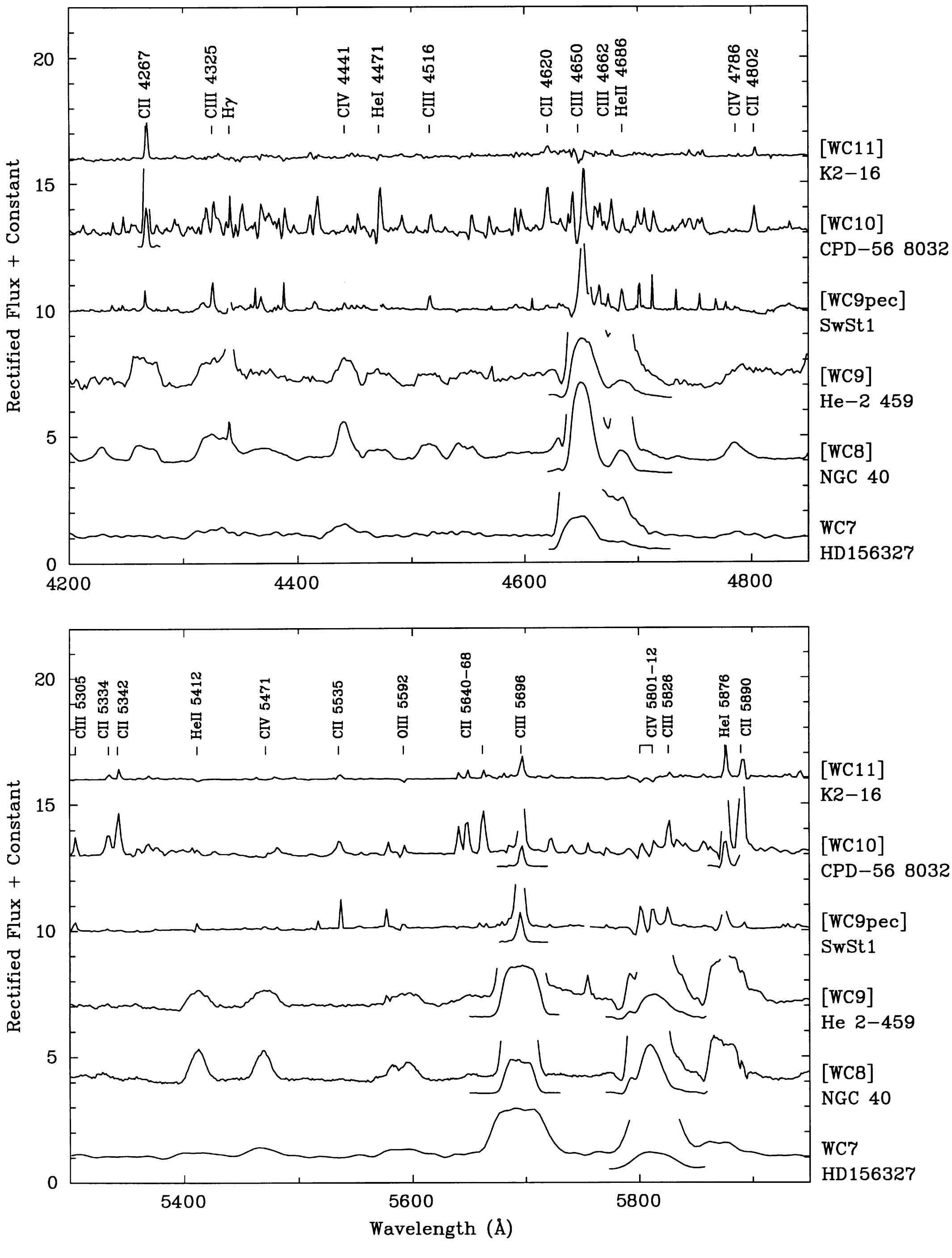

Figure 2. Spectral comparison of WC7–11 stars in the ranges λλ4200–4850 and λλ5300–5950, sorted by new spectral type, demonstrating the change in ionization. Spectra are rectified, separated by 3 continuum units, with very strong lines shown divided by 4, offset by 0.5 continuum units, for clarity.

λ4542/He I λ4471 ratio and absence of Si III λλ4552–4573. A Iab supergiant luminosity class is implied from the observed C III λ5696 emission coupled with He II λ4686 absorption (Walborn, private communication). However, since it has strong infrared emission bands, attributed to polycyclic aromatic hydrocarbons (Beintema et al. 1996), with a symmetric mid-infrared dust nebula, it is almost certainly a young H-deficient CSPN.

Optical spectra of the hot R CrB star V348 Sgr have previously been discussed by Leuenhagen et al. (1994). On the basis of the Hu & Bibo (1990) scheme, they suggested a [WC12] classification because C II emission is present and C III–IV and He II are absent. They commented on the similarity of its absorption-line spectrum to those of extreme He stars (e.g. DY Cen). Since C III λ5696 is absent in V348 Sgr (Dahari & Osterbrook 1984), it *fails* our WCL criteria: the ionization state is too low (20 kK, according to Leuenhagen & Hamann 1994). In support of this exclusion, we recall the original definition of a WR star from Beals (1938): 'emission bands due to atoms of *high* ionization potential' are required. We suggest an alternative, although not completely satisfactory, classification for this unique object of 'peculiar extreme He star'. Exclusion of such

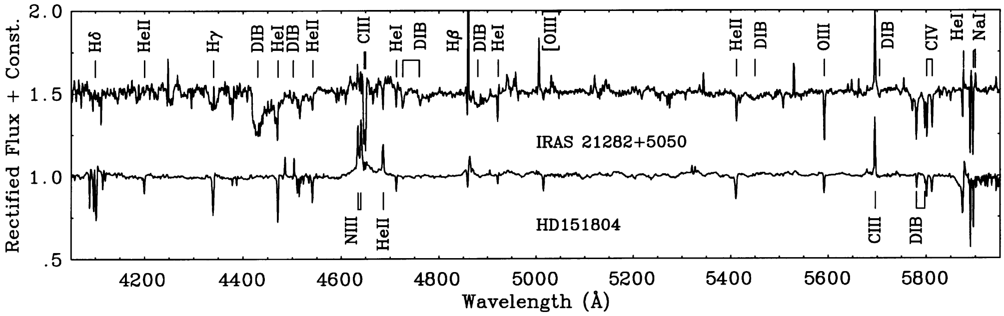

Figure 3. Spectral comparison of IRAS 21282+5050, previously classified as WC11 (Cohen & Jones 1987), with HD 151804 (O8 If, Crowther & Bohannan 1997) showing an extremely similar spectral morphology in the yellow, though differing substantially in the blue (especially around He II λ4686), probably as a result of abundance differences. Note the presence of strong diffuse interstellar bands (DIBs) at λλ4430, 4760, 4880, 5780 and 5797 (Herbig 1995).

low-ionization spectral types from the WC sequence is analogous to that of lower ionization stars from the WN sequence (which extends to WN11 provided that He II λ4686 emission is present); such stars are given P Cygni-type (B Ia$^+$) classifications.

4 CLASSIFICATION OF WCE AND WO STARS

High-excitation WC-type CSPNe are presently classified on a different scheme (MN) from Population I WC and WO stars (SSM; KBS). In this section we investigate whether the classification schemes can be, or indeed should be, unified.

4.1 Current WCE and WO schemes

For high-ionization CSPNe showing negligible C III λ5696 emission, MN suggest classification into WC2–4 subtypes using diagnostic lines: O V λ5590, O VI λ5290 and O VII λ5670. For the Population I Sanduleak (1971) stars that show extremely strong O VI λλ3811–34 emission, Barlow & Hummer (1982) introduced the WO subclass; this sequence was later quantified by KBS using the diagnostics O IV λ3400, O V λ5590 and C IV λλ5801–12. Population I stars without strong O VI emission are left in the WC4 subclass of SSM. *The three schemes yield different classifications for the same spectrum*: e.g. NGC 6905 would be classified [WC3] in the scheme of MN, [WC4] in the scheme of SSM, and [WO2] in the scheme of KBS.

Fig. 4 plots equivalent width ratios of our programme WCE CSPNe, supplemented by six WO stars (KBS), three WC4 stars in the Galaxy and five WC stars in the Large Magellanic Cloud (Torres & Massey 1987). The horizontal axis shows the ionization ratio W_λ(O VI λ5290)/W_λ(O V λ5590) of the MN scheme, while the vertical axis indicates the primary WO criterion of KBS, namely W_λ(O VI λλ3811–34)/ W_λ(C IV λλ5801–12). Clearly, depending on one's preference, individual stars may presently be assigned either a WCE or a WO spectral classification.

Both schemes have limitations. The primary WO1–5 diagnostic of KBS is an O/C ratio, and will be affected by both ionization and C/O abundance. From Fig. 4 it is clear that it does not separate WO stars, such as Sand 5, from ultra-high-ionization CSPNe, such as NGC 6905. The complex qualitative scheme of MN does successfully distinguish between Sand 5 and NGC 6905, but does not separate WO from WC4 stars.

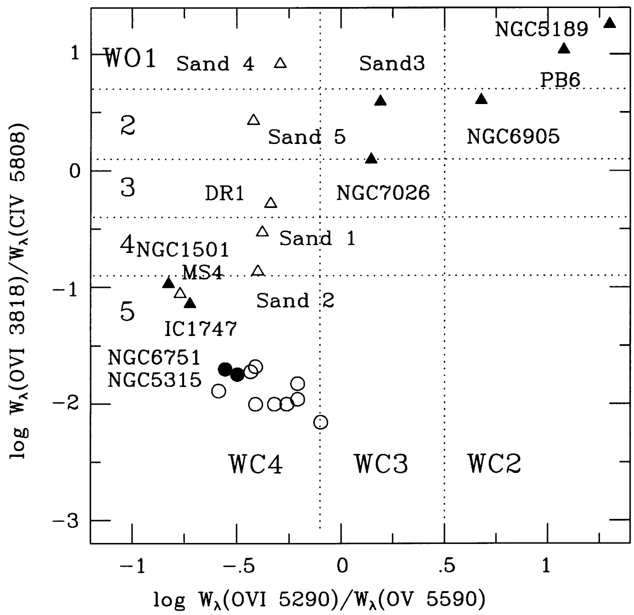

Figure 4. Emission-line equivalent width ratios for the principal classification criteria for WCE stars according to MN, namely O VI λ5290/O V λ5590, versus the principal criteria for WO stars according to KBS, namely O VI λλ3811–34/C IV λλ5801–12. WC4 stars are presented as circles, WO stars as triangles, with filled (open) symbols for CSPNe (Population I stars). Clearly, an individual star can be assigned different spectral types and classes on the basis of the different schemes followed.

4.2 Is a unified classification scheme appropriate?

The classification scheme that we will suggest below is based on ionization only. Before suggesting that the same scheme be applied to both Population I stars and CSPNe, it is appropriate to consider whether we either expect or observe significant abundance differences.

In massive WCE and WO stars, carbon and oxygen are produced continuously in the non-degenerate He-burning core, and are exposed by mass-loss stripping. In CSPN, carbon and oxygen are produced during thermal pulses that last ~10 per cent of the time, at the degenerate bottom of the He shell; carbon and oxygen are dredged up to the surface when the H shell is ejected. The O/C ratio that results is critically dependent on the temperature and density of the He-burning zone. Fig. 4 shows that the O/C line ratios of the two groups of stars are similar, suggesting that the abundances ratios are comparable and implying that the temperature and density of the respective formation zones are also similar.

While the O/C ratios may be similar in these widely different stars, the abundance ratios of (C+O)/He are definitely expected to

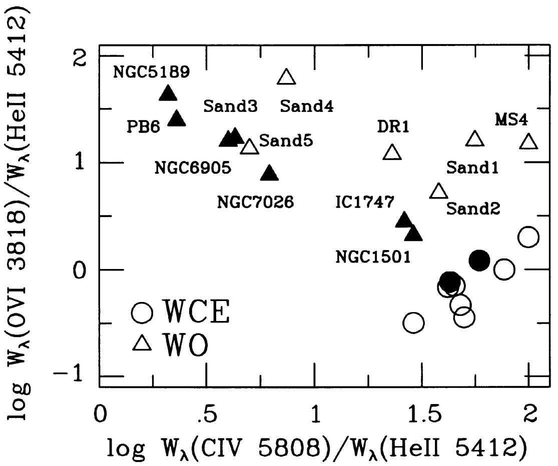

Figure 5. Comparison between the equivalent width ratios W_λ(C IV λ5805)/W_λ(He II λ5412) and W_λ(O VI λ3818)/W_λ(He II λ5412) for massive WO and WCE stars (open), and their CSPNe counterparts (filled). This suggests a systematic difference between C/He ratios for massive WO and CSPNe, but not for WCE stars.

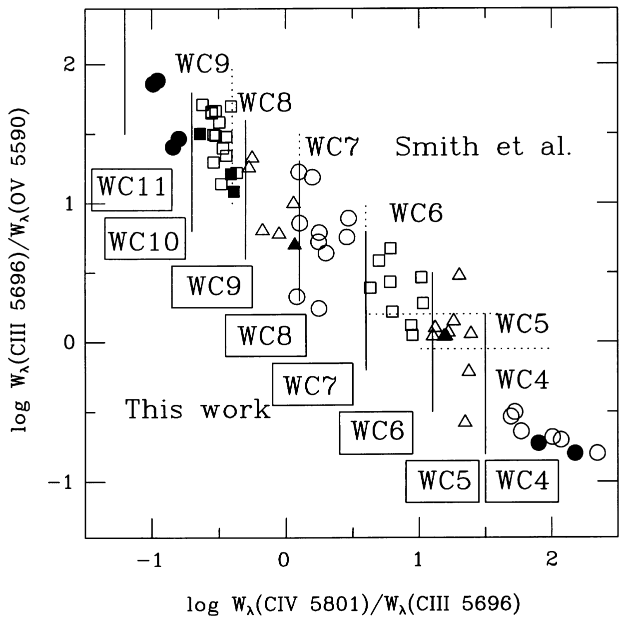

Figure 6. Emission-line equivalent width ratios for both Galactic and LMC massive WC stars (open), and WC-type CSPNe (filled). We follow the principal classification criteria for WCE stars according to SSM, namely C III λ5696/C IV λλ5801–12 versus C III λ5696/O V λ5590. Boundaries of the existing SSM spectral classification are shown (dotted lines) together with our revisions (solid lines, boxed spectral types).

be different, with CSPNe expected to have significantly lower carbon and oxygen enrichment. We might therefore expect lower values of (C+O)/He in CSPNe than in their massive counterparts. We have attempted to test this with the ratio of C IV λ5471/He II λ5412, lines chosen because both are recombination lines and sensitive to abundance. However, the width and weakness of these lines in many of the spectra prohibit a useful comparison. Instead, Fig. 5 plots the equivalent width line ratio of C IV λλ5801–12/He II λ5412 versus O VI λ3818/He II λ5412. Note that the O VI/He II ratio is very sensitive to ionization, but the C IV/He II ratio is less so. For the WCE stars, there appears to be no difference between the line ratios of massive stars and CSPNe. However, the massive WO stars have higher values of C IV/He II at a given O VI/He II ratio than WO-type CSPNe. CSPNe also appear to show a trend of lower C/He at higher excitation, while the massive stars do not. However, excitation effects may play a role in these observations since C V (ionization potential of 392 eV) may be present in WO-type CSPNe. Recall that spectral features of O VII–VIII (739–871 eV) are observed in these stars, potentially influencing the observed C IV/He II ratio, and consequently C/He values.

Koesterke & Hamann (1995), using non-LTE analyses, obtained number fractions of C/He=0.08–0.4 for several massive WCE stars, while Koesterke & Hamannn (1997) derived similar ratios of C/He = 0.13–0.2 for two WCE-type CSPNe, NGC6751 and Sand 3. These results are fairly consistent with the line ratios in Fig. 4, indicating that the carbon enrichment is higher in some massive stars than in any CSPNe. Unfortunately, determinations of the oxygen abundance in massive WCE stars are scarce, with the only quantitative results to date by Gräfener et al. (1998), revealing O/He = 0.05–0.2 for LMC WC4 stars. For comparison, Koesterke & Hamannn (1997) obtained O/He∼0.1 for their WCE-type CSPNe.

4.3 A new classification for WCE and WO stars

Retaining an awareness that there may be a difference in the (C+O)/He ratio between massive stars and CSPNe, we propose a unified classification system that depends primarily on ratios of the same element.

We propose to retain the WC/WO distinction on the grounds that this nomenclature clearly reflects which element dominates the optical spectrum in the same manner that nitrogen dominates the WN spectra and carbon dominates the WC spectra. The dramatic difference between WN and WC stars has been shown to reflect an equally dramatic difference in their surface abundances. The abundance differences between WC and WO stars appear to be much less dramatic. KBS found (C+O)/He ratios in WO stars that are at the upper end of those found for WC stars but there is no discontinuity and very little range in the WO star values. Evolutionary models (e.g. Smith & Maeder 1991) predict a smooth transition, anticipating significantly higher (C+O)/He ratios in WO stars.

It appears that the dominance of oxygen lines in WO spectra is primarily a result of higher ionization, rather than higher oxygen abundance. We therefore favour the adoption of WO subclass numbers that reflect a smooth ionization sequence from WC through to WO.

At present, high-excitation WC spectral types are defined up to WC4 (SSM) or WC2 (MN), with WO subclasses defined from WO5 to WO1 (KBS). For late WC stars, SSM used W_λ(C IV λλ5801–12)/W_λ(C III λ5696) as their primary ionization indicator, which we follow here. This provides a well-defined division between subclasses. For WC4–6 stars, the distinguishing criterion used by SSM is W_λ(C III λ5696)/ W_λ(O III–V λ5590). Instead, we propose to retain the carbon ratio as the primary criterion, thus avoiding any influence of different abundances. The change is indicated in Fig. 6, where we compare the equivalent width ratios of these lines for Galactic and LMC massive WC stars, updated from fig. 3 of SSM to include our programme CSPNe. Relatively few reclassifications are needed. LS3 (WR19) is newly reclassified from WC4 to WC5, HD95435 (WR33) becomes WC6 from WC5, and MR112

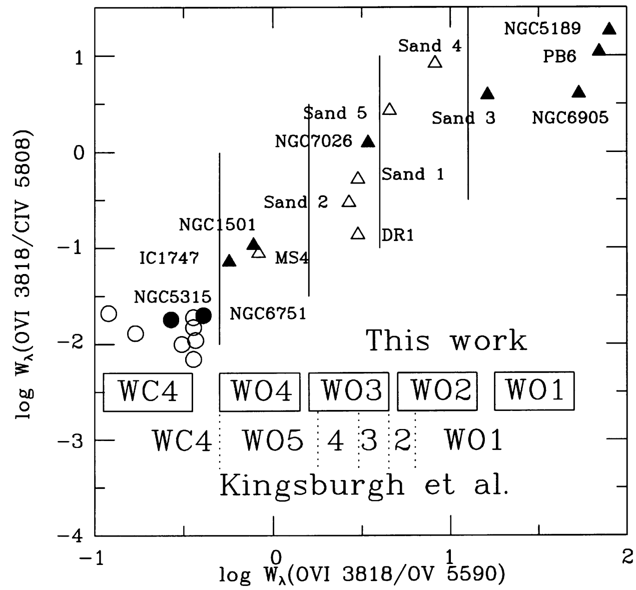

Figure 7. Emission-line equivalent width ratios for massive WO stars (open), and WO-type CSPNe (filled) using the principal classification criteria for WO stars from KBS. Boundaries of existing spectral types are shown (dotted lines), together with our revisions (solid lines, boxed spectral types).

(WR146) is newly reclassified from WC6 to WC5. Spectral peculiarities of LS3 and MR112 have previously been remarked upon by SSM and Eenens & Williams (1994). Our complete WC spectral classification definitions are indicated in Table 3.

An appropriate criterion to separate WO from WC appears to be the absence of C III λ5696 (as proposed by KBS). Without this line, the WC criteria fail and WO diagnostics, depending on oxygen lines, take over smoothly. Fig. 7 shows the two equivalent width ratios used by KBS, for the same stars as in Fig. 4. The two criteria are well correlated, but will give different results because of the scatter. KBS chose W_λ(O VI λλ3811−34)/W_λ(C IV λλ5801−12) as their primary criterion. This ratio fails to separate spectra at the high-ionization end, despite great differences in the dominant oxygen ion. It also has the disadvantage that it can be affected by O/C abundance variations. We therefore choose W_λ(O VI λλ3811−34)/W_λ(O V λ5590) as the primary subclass criterion.

Because O VI λλ3811−34 is seriously affected by interstellar reddening, we have searched for suitable diagnostics in the yellow–red part of the spectrum (e.g. O VI λ5290), but find that O VI λλ3811−34 is indispensable. (O IV λ3400 provides an excellent diagnostic for WO stars but it is even more difficult to observe.) If O VI λλ3811−34 is unavailable, the ratio W_λ(O VI λ5290)/W_λ(O V λ5590) in excess of unity appears to be a reliable indicator of ultra-high-excitation WO-type CSPNe (WO1 in the new system).

Fig. 7 shows the KBS subclass boundaries in W_λ(O VI λλ3811−34)/W_λ(O V λ5590). These have several disadvantages: (i) the range of each subclass is very small, ~0.2 dex, leading to a very small number of stars in each subclass; (ii) nothing distinguishes between Sand 4 and the higher excitation stars like NGC 6905; (iii) current subclass names fail to indicate that WO5 stars are of equal or higher ionization than WC4 stars. We therefore consider it useful to redefine the boundaries, commencing with WO4 at the low-excitation end, and proceed in nearly equal intervals to WO1 at the high-excitation end. Overlapping subclass numbers, WC4 and WO4, appear acceptable since the degrees of ionization of these two subclasses are very similar; the primary difference between them is the strength of the O VI λ3818 feature. The result is a nomenclature scheme that is simple, intuitive and physically meaningful.

Boundaries between WO subclasses have been chosen to correspond with the presence or absence of other oxygen ionization stages. Although WO subclasses are defined according to their

Table 4. Revised spectral classifications for WC- and WO-type CSPNe, including several stars from previously published spectroscopy. We include subtypes from the literature – Smith & Aller (1969, SA69), MN, Heap (1982, H82), Hu & Bibo (1990, HB90), and Tylenda et al. (1993, T93).

Name	PN G	SA69	MN	H82	HB90	T93	Others	This work
SwSt1	001.5−06.7	WR-Of	WC9		WC10	wel	Of-WR(C)[b]	WC9pec
M1−25	004.9+04.9					WC6?	WC6[a]	WC5
IRAS 17514−1555	012.2+04.9				WC11			WC10
NGC 6751	029.2−05.9			WC4-N4/OVI		WC4		WC4
NGC 6905	061.4−09.5		WC3	WC2/OVII		WC3		WO1
BD+30°3639	064.7+05.0	WC9	WC9	WC9		WC9		WC9
He 2−459	068.3−02.7					WC9		WC9
NGC 7026	089.0+00.3		WC3	WC2/OVII		WC	WC3/4[a]	WO3
NGC 40	120.0+09.8	WC8	WC8	WC8		WC8		WC8
IC 1747	130.2+01.3		WC4	WC4/OVI		WC	WC4[a]	WO4
NGC 1501	144.5+06.5			WC4/OVI		WC4		WO4
M4−18	146.7+07.6				WC11	WC11		WC10
PB6	278.8+04.9					WC3?	WC3/OVI[a]	WO1
IRAS 07027−7934	291.3−26.2						WC11[c]	WC10
NGC 5189	307.2−03.4		WC2	WC2				WO1
He 2−99	309.0−04.2	WC9	WC9			WC9		WC9
NGC 5315	309.1−04.3		WC4	WC6		WC4		WC4
He 2−113	321.0+03.9				WC11	WC11		WC10
CPD−56° 8032	332.9−09.9			WC10	WC11	WC11		WC10
K2−16	352.9+11.4					WC11		WC11
Sand 3			WC3					WO1
IRAS 21282+5050							WC11[d]	O9−9.5

[a]Acker et al. (1996); [b]Méndez et al. (1991); [c]Menzies & Wolstencroft (1990); [d]Cohen & Jones (1987)

Table 5. Spectral classifications for massive WC and WO stars, including those stars revised relative to SSM and KBS. We include many stars from previously published spectroscopy (Torres & Massey 1987), and compare with subtypes from the literature (van der Hucht et al. 1988, vdH88). All existing LMC WC4 stars are unaffected.

WR	Star	vdH88	SSM	KBS	This work
19	LS3	WC4	WC4		WC5
29a	MS4	WC4+a	WO4+O4	WO5+O4	WO4+O4
33	HD 95435	WC5	WC5		WC6
52	HD 115473	WC5	WC4		WC5
53	HD 117297	WC8	WC8		WC9
102	Sand 4	WO1	WO1	WO1	WO2
142	Sand 5	WO2	WO2	WO2	WO2
146	MR112	WC4	WC4		WC5
Br93	Sand 2			WO4	WO3
AB8	Sand 1			WO4	WO3
	DR1			WO3	WO3

W_λ(O VI λλ3811–34)/W_λ(O V λ5590) ratio, as summarized in Table 3, secondary criteria are as follows:

(i) WO4 stars show W_λ(O VI λλ3811–34) $\ll$ W_λ(C IV λ5801–12);

(ii) WO3 stars have $0.1 \leq W_\lambda$(O VI/C IV)≤ 1.5, with O VII λ5670 weak or absent;

(iii) WO2 stars have W_λ(O VI/C IV)≥ 1.5 and W_λ(O VII λ5670/O V λ5590)≤ 1;

(iv) WO1 stars have W_λ(O VII λ5670/O V λ5590)≥ 1, plus the presence of O VIII λ6068.

Table 4 gives, for all programme CSPNe, the spectral types on the new system, together with previous classifications from the literature. Table 5 gives the same information for massive WC and WO stars. We provide spectral classifications for ~50 per cent of the known Galactic WC- and WO-type CSPN population (Tylenda et al. 1993). Additional stars are predominantly of WCE or WO spectral type, with only three other WCL stars known (M2–43, He 2–142 and Pe1–7: Tylenda et al.). New spectral classifications for these stars await reliable optical spectroscopy.

Fig. 8 presents rectified spectra of our programme WC4 and WO1–4 CSPNe. We include, for comparison, a WC5 star (HD 165763, WR 111), a WC6 star (HD 92806, WR 23) and Sand 4 (WR 102), re-classified here to WO2. NGC 6751 ([WC4]) is the only one in our sample of high-excitation CSPNe that resembles the very strong emission profiles of massive WCE stars. However, other WCE-type CSPNe are known that also exhibit this characteristic (e.g. NGC 5315: Hamann 1996). Thus, while the CSPNe in Fig. 8 mostly appear to be weaker and sharper lined than the massive star spectra in the same subclass, this cannot be used as a reliable distinction between CSPNe and Population I WCE stars.

Additional criteria are necessary to distinguish between WCE or WO stars and other emission stars. In particular, C IV λλ5801–12 emission is not restricted to WC- or WO-type CSPNe. C IV λλ5801–12, O VI λλ3811–34 and λ5290 emission is observed in Abell 78 (PN G 081.2−14.9: Smith & Aller 1969). This star currently possesses a variety of spectral classifications, namely Of–WR(C) (following Méndez et al. 1991), [WC]–PG1159 (Hamann 1996) and 'weak emission line' (Tylenda et al. 1993). Although optical emission features in this star are extremely weak [W_λ(C IV λ5808)$\leq$15 Å], a [WO1] spectral type is obtained for Abell 78 from our primary criteria presented in Table 3, despite weak/absent O VII–VIII. We therefore propose to restrict bona fide WCE or WO spectral classifications to those stars showing sufficiently strong emission lines, in particular W_λ(C IV λλ5801–12)$\gg$10 Å. Clearly the present classification system for stars with a weak emission-line spectrum is far from satisfactory. Since Abell 78 shows several charactistics in common with both WO stars and PG 1159 stars (high temperature, high gravity, pre-white dwarfs), we tentatively propose a hybrid [WO1]–PG 1159 classification for this star. Any further revisions are beyond the scope of the current work.

4.4 Can we distinguish between WC and WO stars from line widths?

Since O VI λλ3811–34 may be unavailable in heavily reddened objects, it is desirable to have alternative criteria at longer wavelengths to distinguish between WO and WC4 stars SSM and Smith & Maeder (1991) proposed that, since the Sanduleak (1971) WO stars show extremely broad emission lines relative to WC stars, FWHM (C IV λλ5801–12)= 90 Å represented a suitable division between the two sequences. However, Willis, Schild & Smith (1992) found that this represented a poor discriminator, at least for WR stars in M33, since line widths were observed to be metallicity-dependent. In Fig. 9 we compare FWHM(C IV λλ5801–12) with our primary WO diagnostic for massive WC4 and WO stars in our Galaxy, the Magellanic Clouds and IC 1613, plus CSPN counterparts. Although the Sanduleak (1971) WO stars show extremely broad spectral features (FWHM~140±25 Å), DR1 in IC 1613 shows a relatively normal line width (FWHM~72 Å) relative to WC4 stars (FWHM~60^{+30}_{-20} Å). We therefore support the results of Willis et al. (1992) that it is not possible to distinguish cleanly between WO and WC4 stars in the optical without spectroscopic observations at O VI λλ3811–34. However, we note that the WO-type CSPNe under investigation here do show systematically lower line widths than massive WO stars, with FWHM(C IV λλ5801–12)~70 Å representing an approximate division. More definite conclusions await a more complete sample.

4.5 Can we distinguish between Population I stars and CSPNe?

No criterion considered above appears able definitively to separate Population I stars from CSPNe. However, CSPNe display a wider range in some properties, which we now discuss.

Line width. Population I WC and WO stars have consistently broad lines, and the line width is fairly well correlated with ionization subclass; CSPNe, especially WO-type, have narrower lines than their Population I counterparts.

Line strength. Population I WC and WO stars have consistently strong lines; WO-type CSPNe have much weaker lines.

Ionization subclass: The distribution across the subclasses is very different. Massive WC stars are observed only in ionization subclass WC9 to WO2. Later subclasses WC10 and 11 and ultra-high-ionization WO1 stars, the so-called 'O VIII sequence' (Feibelman 1996), are found only in CSPNe. Conversely, CSPNe are rare in the middle subclasses: zero out of 12 stars have WC6 or WC7 subclasses. compared with 19 out of 55 in our sample of massive WC stars. This is illustrated in Fig. 6.

5 SUMMARY

We have presented new observations of WC- and WO-type central

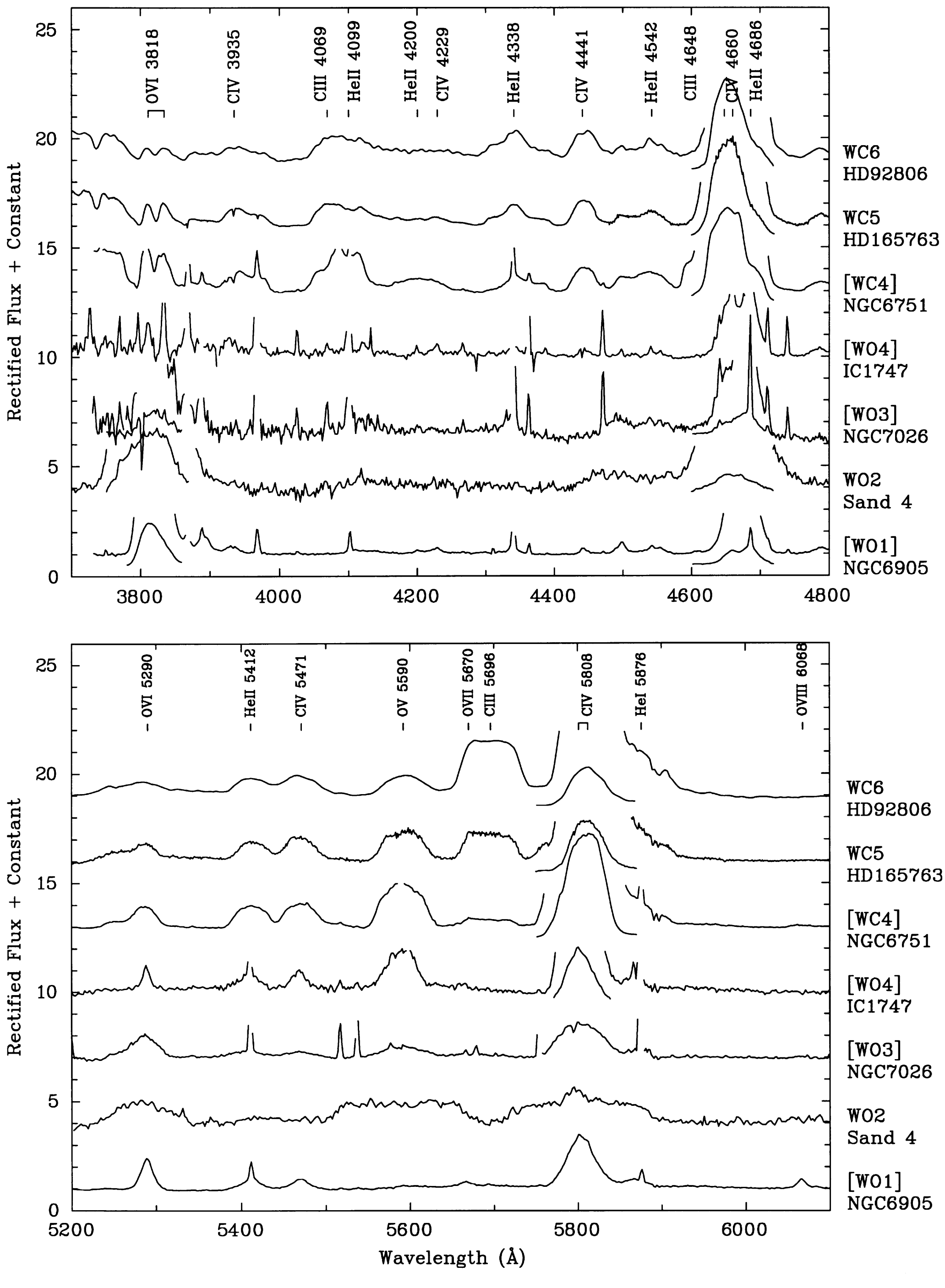

Figure 8. Spectral comparison of WO1–4..WC4–6 stars in the ranges λλ3700–4800 and λλ5200–6100, sorted by spectral type, demonstrating the change in ionization. Sharp emission lines are of nebular origin and include He II λ5412, [Cl III] λ5517–37 and He I λ5876. Spectra are rectified, separated by 3 continuum units, with very strong lines shown divided by 5 (10 for C IV λ5808 profiles for WC4–6 stars), offset by 0.5 continuum units, for clarity.

stars of planetary nebulae and classical Wolf–Rayet stars, their more massive counterparts. A unified classification scheme has been developed that depends primarily on line ratios of the same element. It provides an unambiguous definition of spectral subclass for all stars. In increasing order of excitation, our spectral subclasses range from WC11 to WC4 for Wolf–Rayet stars with carbon lines dominant, and subsequently from WO4 to WO1 for those with oxygen lines dominant. The continuity of the subclass numbers from WC to WO is used to indicate that the sequence is due primarily to excitation, rather than abundance. No criterion has been found that definitively distinguishes CSPNe from more massive stars. However, the CSPNe display a greater diversity in line width and strength than the massive stars.

Our unified scheme provides an objective method of comparing the subclass distributions of massive Wolf–Rayet populations and CSPNe. Our results support previous suggestions that there is a significant absence of WC-type CSPNe at intermediate excitation (Tylenda et al. 1993). The sparsity of CSPNe in subclasses WC6–8

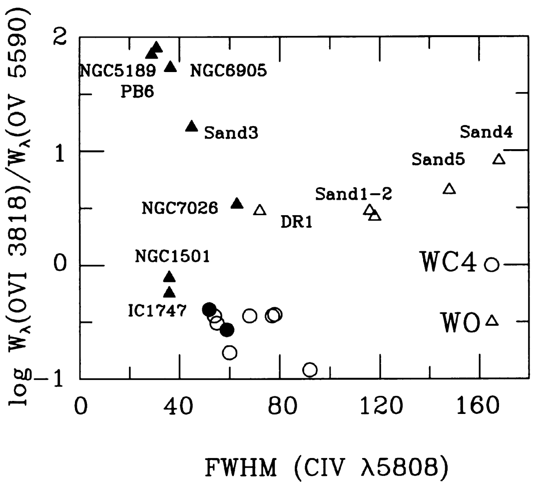

Figure 9. Comparison between FWHM(C IV λλ5801–12) versus our primary WO spectral diagnostic W_λ(O VI λ3811–34)/W_λ(O V λ5590) for massive WO and WC4 stars (open), and their CSPN counterparts (filled). This shows that we are unable to distinguish between massive WO and WC4 stars on the basis of FWHM(C IV λλ5801–12) alone. However, all massive WO stars show a reasonable separation from CSPNe using their FWHM(C IV λλ5801–12).

indicates either a rapid evolution through this range, or a different evolutionary path leading to the two extremes of the ionization sequence. Detailed abundance studies are needed, in order to verify our suggestion that the C and O abundances in the massive and CSPN WC-type stars are comparable.

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