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The spectra of WC9 stars: evolution and dust formation*

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ABSTRACT

We present analyses of new optical spectra of three WC9 stars, WR 88, WR 92 and WR 103 to test the suggestion that they exemplify an evolutionary sequence amongst the WC9 stars. The spectrum of WR 88 shows conspicuous lines of N III and N IV, leading to classification as a transitional WN8o/WC9 star. The three stars show a sequence of increasing O II and O III line strengths, confirming and extending earlier studies. The spectra were analysed using CMFGEN models, finding greater abundances of oxygen and carbon in WR 103 than in WR 92 and, especially, in WR 88. Of the three stars, only WR 103 makes circumstellar dust. We suggest that oxygen itself does not enhance this process but that it is its higher carbon abundance that allows WR 103 to make dust.

Key words: stars: abundances – stars: individual: WR 88 – stars: individual: WR 92 – stars: individual: WR 103 – stars: Wolf–Rayet.

1 INTRODUCTION

Population I Wolf–Rayet (WR) stars represent the last stable stage in the evolution of massive stars and are characterized by dense, fast stellar winds giving the stars broad emission-line spectra and carrying heavy mass-loss. The winds expose the stars' hot cores and have compositions influenced by nuclear processing in the stellar interiors. The WR stars appear to follow an evolutionary sequence, with WN stars showing the products of CNO-cycle burning, and WC stars the products of He-burning. Overall, the measured H/He/N/C/O abundances in the different classes of WR star are consistent (Crowther 2007, and references therein) with the predictions of modelling the evolution of massive stars with mass-loss and the consequent stripping of their outer layers. Another mechanism for stripping the outer layers of stars and forming WR stars is mass transfer in binary systems, and the relative importance of these two channels for the formation of WR stars remains a vigorously debated question.

Mass-loss depends on the WR stars' overall metallicities, primarily iron-group elements inherited from the local interstellar medium, and, amongst the WC stars in particular, it is observed that stars of different spectral subtype are more prevalent in environments of different ambient metallicity. Metal-poor environments, e.g. the Small Magellanic Cloud, produce 'early' subtype (WC4) stars; whereas stars of the 'latest' subtypes (WC9–10) are found *only* in metal-rich regions, such as the inner regions of our Galaxy. Indeed, many more WC9 stars are being discovered from surveys, many in the infrared (IR), and studies of embedded star clusters (e.g. Negueruela & Clark 2005; Mauerhan, van Dyk & Morris 2009; Shara et al. 2012) in the inner regions of the Galaxy.

A survey of the optical spectra of WC9 stars by Torres & Conti (1984) found them to be rather homogeneous (apart from WR 88 discussed below), and showing no evidence for binary companions to the WC9 stars. The question of binarity amongst WC stars has since been stimulated by the association of the formation of carbon dust in the winds of most WC9 stars and a few of earlier spectral subtype with colliding stellar winds in WC+O binaries. This association began with the observation that the periodic episodes of dust formation by the WC7pd+O5.5fc binary WR 140 coincided with periastron passage in its highly eccentric orbit (Williams et al. 1990), and the demonstration that efficient radiative cooling of the shock-compressed wind could lead to dust formation (Usov 1991) in this system. The association was extended to the persistent dust makers amongst the WC9 stars by the observation of a rotating pinwheel of dust emission formed by WR 104 (Tuthill, Monnier & Danchi 1999), interpreted as a collimated plume of dust formed by a binary observed at low inclination angle, and subsequently modelled by Harries et al. (2004).

Such results raise the question of whether membership of a colliding wind binary (CWB) is *necessary* for dust formation by WR systems; a process still unexplained four decades after its initial discovery. To examine the question of binarity amongst WC9 stars

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more closely, the blue–violet spectra of a sample of WC9 stars were observed with the 1.9-m telescope at the South African Astronomical Observatory (SAAO) to search for absorption lines attributable to hot companions. A by-product of this study (Williams & van der Hucht 2000, hereafter Paper I) was the discovery that the spectra of two WC9 stars (WR 81 and WR 92), which had never (in 20+ years of IR photometry) shown IR emission characteristic of dust emission, differed from the other WC9 stars in the sample (all of which were dust makers) in having weaker O II (relative to C II), and stronger He II lines. If these spectroscopic differences were really caused by a lower abundance of oxygen, this could inhibit dust formation by these stars if the formation of CO was on the WC dust-condensation pathway. Even if O is not required on the chemical pathway to dust formation, the dust-free WC9 stars might be less evolved chemically than the dust makers, and this could inhibit dust formation.

The survey of WC9 spectra in the blue was extended using the ESO Multi-mode Instrument (EMMI) on the ESO New Technology Telescope (NTT) at La Silla in 2001 June, identifying two more probable WC9 binaries, WR 59 and WR 65, from absorption lines in their spectra (Williams, van der Hucht & Rauw 2005). The observations of WR 88, another WC9 star having a long photometric history (Paper I) showing no dust emission, confirmed the relative weakness of O II in its spectrum originally noted by Torres & Conti (1984), and also confirmed by Eenens & Corral (2003). Lines of N III–IV were identified in its spectrum, showing that WR 88 either had a WN companion to the WC9 star or was of a previously unobserved transitional WN/WC9 subtype; Williams et al. (2005) preferred the latter alternative because the N lines had comparable widths to the C lines.

The transitional WN/WC stars represent a short-lived evolutionary phase during which the mixing layer containing both H- and He-burning products is exposed by mass-loss. The fractional ratio of the number of WN/WC stars depends on the duration of the WN/WC phase, which depends on the extent of the mixing zone and the mass-loss rate. Initially, most of the known WN/WC stars had very early subtype WC spectra apart from one WC7 spectrum (Conti & Massey 1989). This implied a very strong dependence on WC subtype for the duration of the transitional phase, reflecting significantly higher mass-loss rates and/or thinner zones of mixed material in the stars evolving to the underrepresented later subtypes. The identification of some WN/WC stars, including WR 88, having WC9 spectra goes some way to redressing the imbalance. Another transitional WN/WC star with WC9 features was proposed with the reclassification of the source GC IRS 15SW (= WR 101h; van der Hucht 2006) as WN8/WC9 by Paumard et al. (2006). A spectrum of this source showing weak N III lines at 2.247 and 2.251 µm was published by Martins et al. (2007); who also re-classified another Galactic Centre (GC) source, GC IRS 7SW (= WR 101dc), as WN8/WC9. We will return to these WN8/WC9 stars in Section 4.2. Unfortunately, the two-micron spectrum of WR 88 observed by Eenens, Williams & Wade (1991) was too noisy to show the 2.25-µm N III lines.

We therefore observed further spectra of WR 88, WR 92 and WR 103 to cover the diagnostic lines for quantitiative spectroscopic analyses to test whether WR 88 is a transitional WN/WC9 star rather than a WN+WC9 binary and whether the weaker O II lines in the dust-free stars like WR 92 are caused by lower O abundances. This would support the suggestion of an evolutionary sequence amongst the WC9 stars as exemplified by WR 88 → WR 92 → WR 103, especially if the lower O abundances were accompanied by lower C/He abundance ratios. The well-studied WC9 star WR 103 (Crowther, Morris & Smith 2006, hereafter C06, and references therein) was used as a baseline. This star is 'light' dust-maker, as measured by the fraction of stellar luminosity re-radiated by dust in the IR (1.2 per cent; Williams, van der Hucht & Thé 1987), and the ratio of the 4415-Å O II to 4267-Å C II) line strengths in its spectrum is typical for the dust-makers (Fig 1). The analysis of WR 103 by C06 fitted the spectrum from the ultraviolet to the mid-IR whereas the analysis in this present paper will consider only the spectral regions common to all three stars all observed at the same resolution to study their relative compositions. Sander, Hamann & Todt (2012, hereafter S12) included WR 88, WR 92 and WR 103 in their analyses of a large sample of WC stellar spectra using the POWR (Potsdam WR; e.g. Gräfener, Koesterke & Hamann 2002) code, but adopted for the WC9 stars the same composition, He:C:O of 55:40:5, used for most of the WC stars they studied.

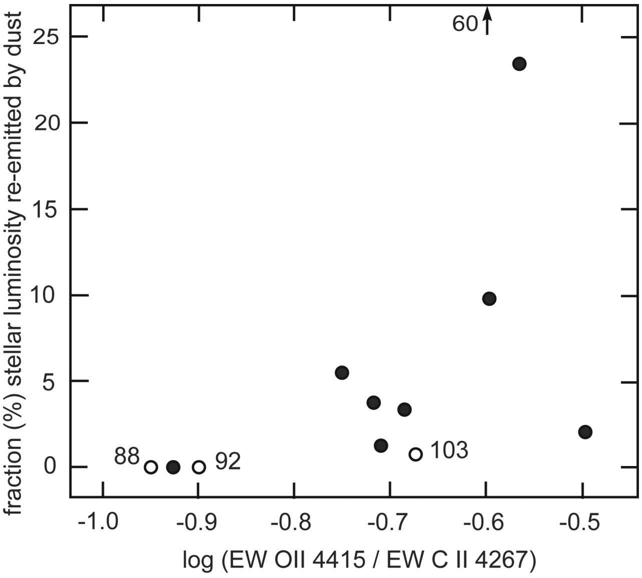

Figure 1. Percentage of stellar luminosity re-emitted by dust from Williams et al. (1987) versus ratio of equivalent widths of the 4415-Å O II and 4267-Å C II lines from Paper I and our new spectra; WR 104 re-emits 60 per cent of the stellar flux in the IR and is off scale. The stars analysed in this paper are marked with open circles.

The relatively narrower lines of the WC9 stars, compared with those of earlier subtypes, allow more blends to be resolved and more subtle differences to be observed. This calls for higher resolution spectra than those (∼10 Å) used by S12, and new modelling to search for small differences in chemical composition – a differential analysis, using as far as possible the same spectral lines in each of the stars.

In this paper, we describe observation of the new spectra in Section 2, compare them qualitatively in Section 3.1 and quantitatively using model atmospheres in Section 3.2. In Section 4.1, we discuss WR 88 in the context of the WN/WC transitional stars and their locations in the Galaxy, and in Section 4.2 we consider the possible influence of carbon and oxygen abundances on WR dust formation.

2 OBSERVATIONS

The spectra were observed with the EMMI on the 3.5-m NTT at the European Southern Observatory, La Silla. We used grating #3 and 0.7-arcsec entrance slit to observe 'violet (V)', 'blue (B)' and 'green (G)' spectra in wavelength ranges 3800–4230 Å, 4230–4640 Å and 4570–4980 Å, respectively; grating #6 and 0.8-arcsec slit for

Table 1. Observation log showing wavelength regions (*VBGYR*, see text) observed with EMMI in each season along with the stars' status as dust makers (fraction of stellar luminosity re-emitted in the IR by dust, taken from Williams et al. 1987).

WR	Name	$L_{\rm d}/L_*$	2001	2006
88	CPD-33 4347	0.0	*V*, *B*	*B*, *G*, *Y*, *R*
92	HD 157541	0.0	*V*, *B*	*G*, *Y*, *R*
103	HD 164270	0.012	*V*, *B*	*G*, *Y*, *R*

'yellow (Y)' covering 5290–5930 Å and grating #7 and 0.8-arcsec slit for 'red (R)' spectra covering 5980–7430 Å. These entrance slits gave spectral resolution of 1.1–0.9 Å in the violet–green, 1.6 Å in the yellow and 3.3 Å in the red as measured from the Th–Ar comparison spectra and the interstellar Ca II K line in the violet. An observing log is given in Table 1. Most of the violet and blue spectra were observed on 2001 June 17–19, while the remaining spectra were taken in Service Observing mode on 2006 June 18–19, July 15 and August 20. We observed a red spectrum of LTT 7379 to help remove the telluric lines from the WR spectra.

The spectra were reduced using FIGARO with wavelength calibration from observations of Th–Ar lamps. Owing to the narrowness of the entrance slits used, we did not attempt flux calibration directly. Instead, to put the different spectra of each star on to the same scale and correct for reddening, we scaled our individual spectra of WR 88, WR 92 and WR 103 to match the lower resolution spectrophotometry of these stars by Torres & Massey (1987), which we de-reddened by $A_v = 6.03$, 2.13 and 1.76, respectively (van der Hucht 2001, table 28), where v is on the narrow-band photometric system used for WR stars (Smith 1968b). For the flux scales, we used the synthetic filter v magnitudes measured for these stars by Torres-Dodgen & Massey (1988).

To fill in the 4980–5290-Å gaps between the 'G' and 'Y' spectra, we used spectra of WR 92 and WR 103 observed with the grating spectrograph on the 1.9-m telescope of the SAAO at Sutherland at the time of the Paper I observations in 1995 May. The 1200 mm^{-1} grating and 175-µm slit gave a resolution of 1.2 Å or two channels of the intensified Reticon Photon Counting System (RPCS) detector system; observing and reduction details are given in Paper I. We also used our RCPS spectra of WR 92 and WR 103 to extend the spectral coverage to shorter wavelengths to include the 3760-Å O III lines. The latter spectra were not of the highest quality owing to the relatively low sensitivity of the system near the edge of the detector, so the data were re-gridded to 2-Å bins. We did not observe WR 88 with this instrument and so used a section of the lower resolution spectrum observed by Torres & Massey (1987) to fill in the 4980–5290-Å gap.

3 RESULTS

3.1 The spectra

As expected from the earlier studies, the spectra of the three WC9 stars are rather similar, but closer comparison reveals significant differences.

The new data confirm the presence of WN features in the spectrum of WR 88. We compare selected short regions of its spectrum with that of WR 92, another 'dust-free' WC9 star, in Figs 2 and 3. In these figures, and for the discussion, the spectra have been shifted to correct for their radial velocities. We confirm the relative strength of He II and weakness of C II and C III in WR 88 reported by Torres & Conti (1984), but note that the difference at the position of the 4100-Å He II line is significantly greater than that of the 4200-Å He II line or the 4026-Å He I+II blend (Fig. 2), so He II is not the main

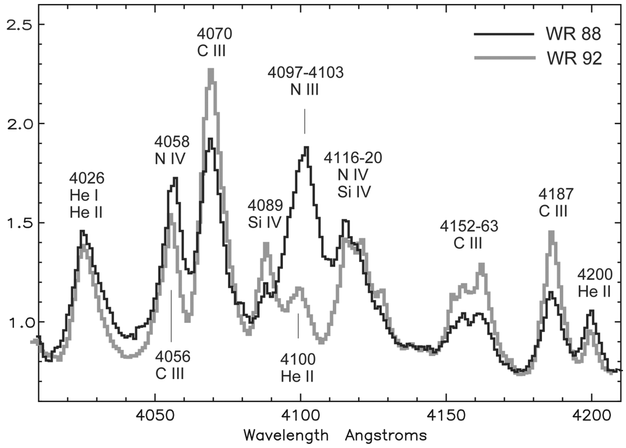

Figure 2. Part of the rectified violet spectrum of WR 88, compared with that of WR 92 (grey), scaled to match that of WR 88 in the 4026 and 4200-Å helium lines, and showing the relative strengths of the 4100 4058 and 4116-Å features discussed in the text.

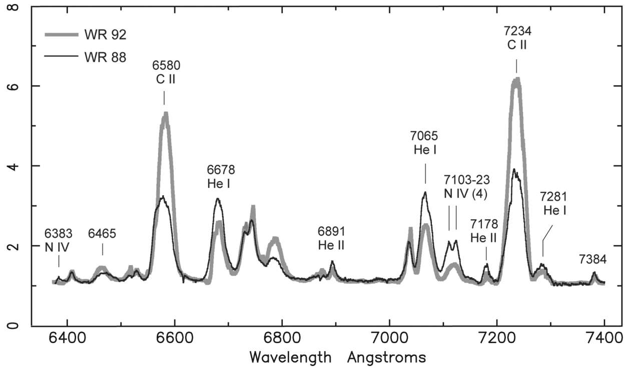

Figure 3. Part of the rectified red spectrum of WR 88 compared with that of WR 92 (grey) to show the region of multiplet 4 of N IV. Also seen at the blue edge of the spectrum is the 6383-Å N IV line.

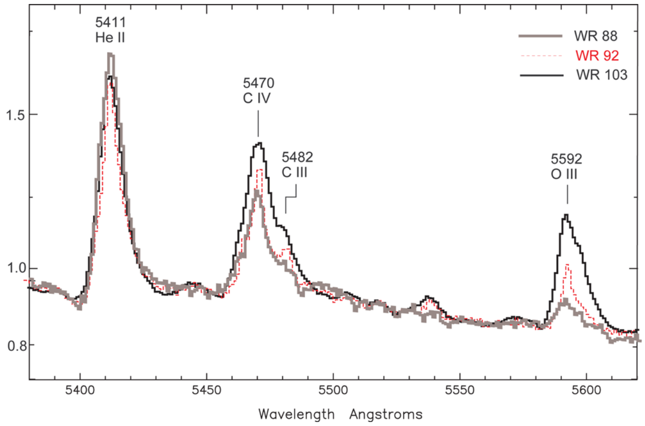

Figure 4. Part of the yellow spectra of WR 103, WR 92 (dotted, red in the online version) and WR 88 (grey) in the region of multiplet 5 of O III to show the relative strengths of this feature in the three stars.

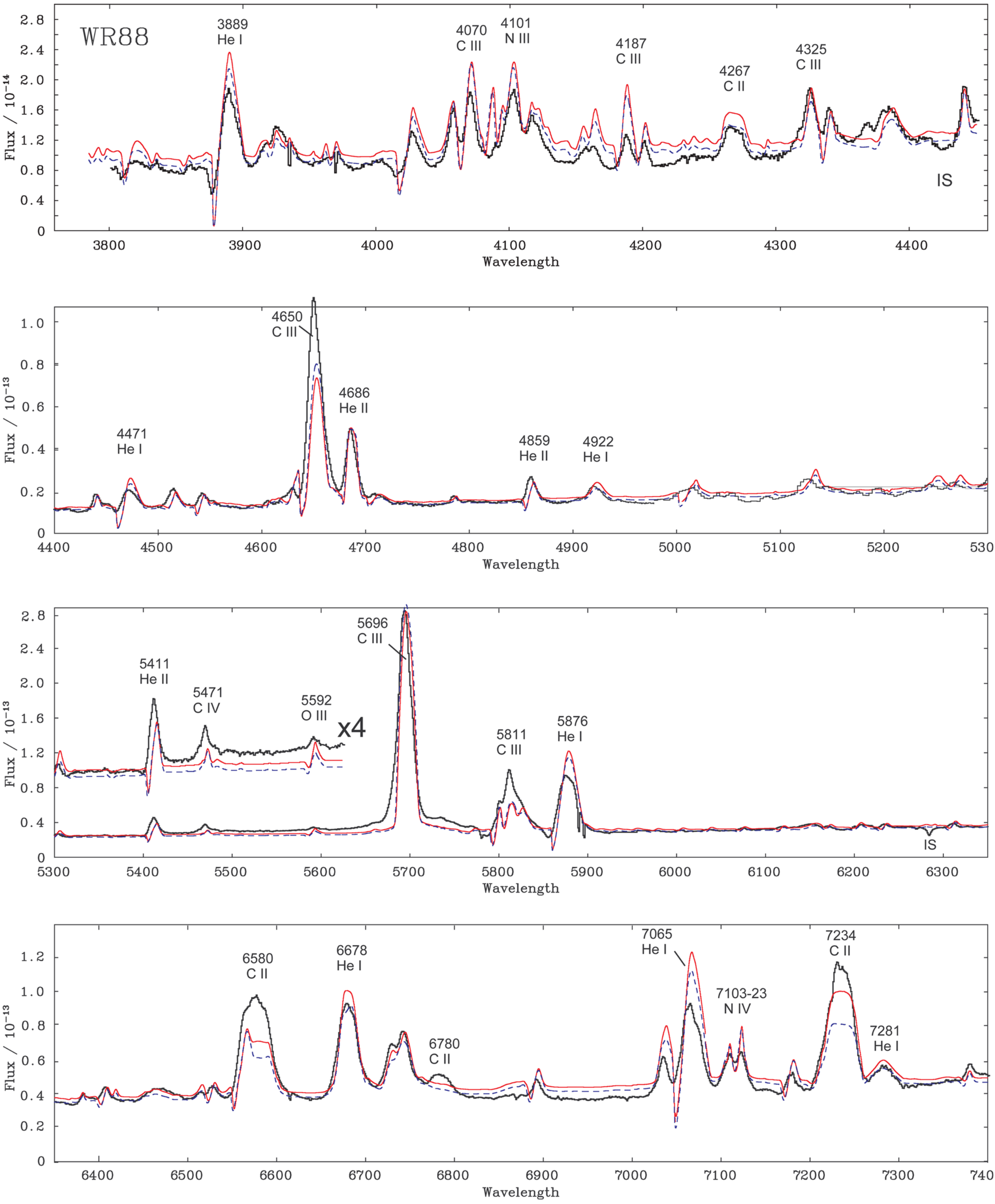

Figure 5. Model spectrum of WR 88 (WN8o/C9) for parameters in Table 2 (continuous line, red in the online version) together with another having $T_* = 42$ kK with the same composition (dashed line, blue online), compared with the observed spectrum (heavier, line stepped). Flux units are erg cm^{-2} s^{-1} Å^{-1}. The region including the 5411-Å He II and 5592-Å O III lines is replotted at higher scale. Some lines are identified; more identifications in the regions of the 4097–4103 N III doublet, and 7103–27 N IV multiplet were given in Figs 2 and 3 comparing WR 88 with WR 92. The diffuse interstellar bands at 4430 and 6284 Å (marked 'IS') are evident in the observed spectrum, as well as Ca II and Na I lines; WR 88 is the most heavily reddened of the three stars.

contributor to the 4100-Å feature in WR 88. Instead, we attribute most of it to multiplet[1] 1 of N III at 4097–4103 Å. This is the strongest accessible N III feature in our data: the 4634–41 Å multiplet used for spectral classification (Smith 1968a) is mostly masked by the strong 4647–51 Å C III triplet, but may still be evident in WR 88. Whereas the C III features in WR 92 and WR 103 have P-Cygni absorption components around 4630–4640 Å, this is filled in our

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[1] Multiplet numbers are from Moore (1959) and Moore & Gallagher (1993).

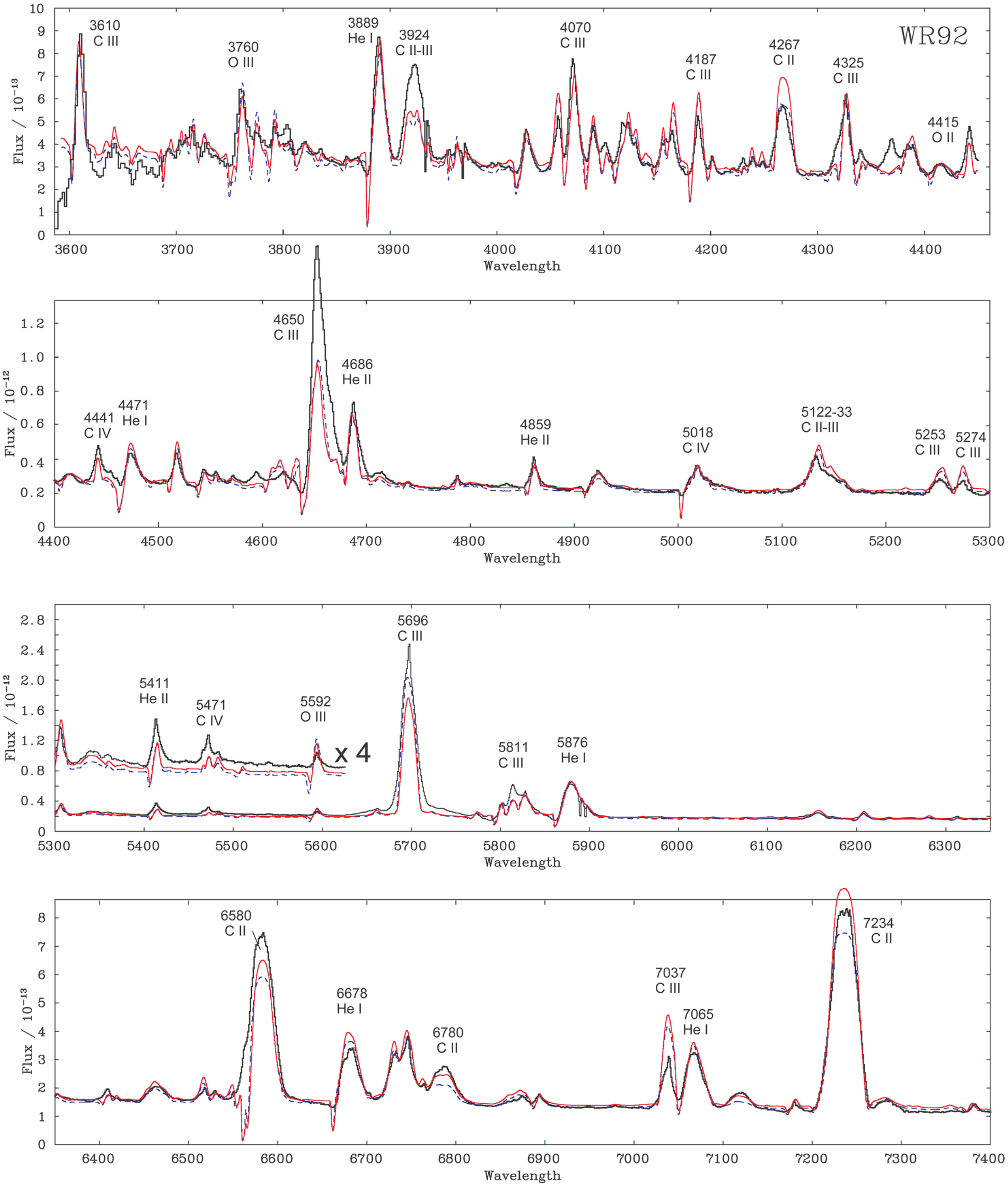

Figure 6. As Fig. 5: model spectrum of WR 92 (WC 9) for the parameters in Table 2, together with another having $T_* = 41$ kK and double the oxygen abundance ($X_{\rm O} = 3$ per cent, dashed line, blue online), compared with the observed spectrum (plotted stepped).

spectrum of WR 88 (cf. Figs 5–7) by a feature near 4630 Å on the edge of the absorption component, which could be the 4634 Å N III line blended with the C III absorption. Comparison of the spectra shows additional emission in the 4515–7 Å C III feature in WR 88 which could be from components of multiplet 3 of N III.

From comparison of the C III lines in Fig. 2, most of which are stronger in WR 92 than in WR 88, we suggest that N IV 4058 Å is a significant contributor to the C III line at 4056 Å in WR 88. The Si IV lines at 4089 and 4116 Å are of comparable strength in WR 92, suggesting that the relative strength of the latter feature in WR 88 comes from the 4116–20 Å triplet of N IV, because the 4089 Å Si IV line in WR 88 is very weak. Confirmation of the identification of N IV in WR 88 comes from the red spectrum (Fig 3), which shows lines from multiplet 4 between 7103 and 7127 Å and probably also N IV at 6383 Å.

The identification of N V is less certain. Torres & Conti noted the strength of the feature at 4603 Å in WR 88 but declined to identify it with N V (as had Smith & Aller 1971 in their analysis of WR 103)

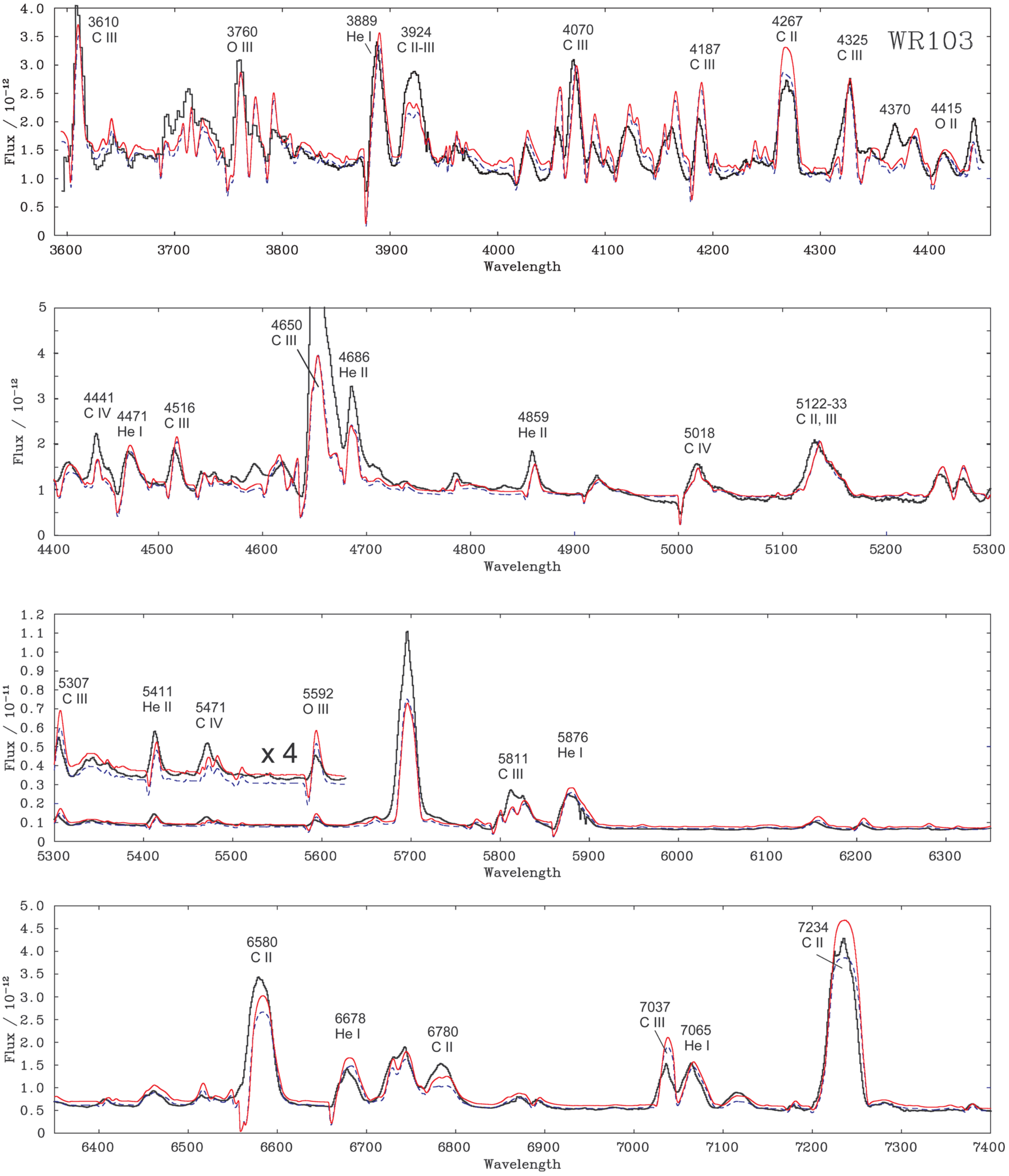

Figure 7. As Figs 5 and 6: model spectrum of WR 103 (WC9d) for the parameters in Table 2 together with another having $T_* = 42$ kK and slightly less carbon ($X_\mathrm{C} = 35$ per cent, dashed line, blue online), compared with the observed spectrum (plotted stepped). The vertical scale in the second panel has been stretched, truncating the 4650-Å C III line, which reached a peak intensity of 7.8×10^{-12} erg cm^{-2} s^{-1} Å^{-1}.

because this ion was unexpected in WC9 stars. The presence of N IV in WR 88 re-opens the question, but our wavelengths for this feature (4605.3–4605.6 Å, from three sprectra) differ from the laboratory wavelength (4603.7 Å) by more than the measurement uncertainties, or velocity of the star as measured from the He II lines, so we do not identify this feature with N V. The other member of multiplet 1 of N V at 4620 Å is masked by O II lines. There might be faint emission at the position of the 4944 Å N V (7–6) array seen in WN stars (Hamann & Koesterke 1998), but not at the position of the (8–7) array (7329 Å), so again we cannot identify N V with confidence.

Nor did we observe N II. Most of the N II lines identified in WN8 and WN9 spectra (Crowther, Hillier & Smith 1995a; Herald, Hillier & Schulte-Ladbeck 2001) are blended with other features in WR 88, but we were able to search for N II emission at 5667 Å – and found none.

A formal classification of the WN spectrum in WR 88 is not possible given the masking of the classification lines by WC9 features, but comparison of the N IV and N III contributions to the 4058 and 4101 Å features, assuming that the WC9 spectrum of WR 88 resembles that of WR 92, with the spectra of the WN8o/C7 star WR 98 and the WN7o and WN8o stars WR 55 and WR 123 presented by Gamen & Niemela (2002) suggests a type of WN8o for the WN lines in WR 88.

The 4416-Å O II lines in WR 88 are weaker than those in the other dust-free WC9 stars and the ratios of this line to the C II 4267-Å and He I 4471-Å lines are smaller than those in WR 81 and WR 92 measured for Paper I, and significantly smaller than the corresponding ratios in the dust-making WC9 stars. As noted above, we observed the region of the 3760-Å O III lines in WR 92 and WR 103 but not WR 88. Instead, we compare our spectra in the region of the relatively unblended 5592-Å O III multiplet in Fig. 4, which shows the most conspicuous differences. This confirms the measurement by Torres & Conti that WR 88 had the weakest 5592-Å line in their sample of WC9 stars. It is evident that the differences in O II lines are mirrored by those in O III, as also shown in the comparison of the 3760-Å O III lines in WR 92 and the dust-making stars WR 53 and WR 96 in Paper I. The interpretation of these differences in terms of abundances is examined in the next section.

3.2 Analysis

Following C06, we employed the CMFGEN code (Hillier & Miller 1998), which solves the transfer equation in the comoving frame subject to statistical and radiative equilibrium, assuming an expanding, spherically symmetric, homogeneous and static atmosphere, allowing for line blanketing and clumping. The model atoms for the analyses of WR 92 and WR 103 contain He I–II, C II–IV, O II–IV, Ne II–IV, Si III–IV, S III–VI, Ar III–V, Ca II–VI and Fe III–VI. For WR 88, a nitrogen model N II-V was added.

For the distances, we used the de-reddened photometry referred to above and adopted $M_v = -4.6$ for WC9 stars from van der Hucht (2001), deriving 2.4, 3.8 and 2.2 kpc for WR 88, WR 92 and WR 103, respectively. We note that S12 adopted for their analyses a higher luminosity for WC9 stars, $M_v = -5.13$, based on that of WR 95, believed to be a member of the open cluster Trumpler 27. As Perren, Vázquez & Carraro (2012) have recently called into question the true nature and location of this cluster, considering it to be a population of stars distributed all along the line of sight with some stellar clumps, we consider the calibration of M_v via that of WR 95 and Trumpler 27 to be insecure. The calibration of M_v for WC9 stars certainly needs strengthening.

A series of models was computed for each star aimed at getting the best fit to the observed spectra. We began by determining the model temperatures from considering fits to the helium and carbon ionization ratios. The He I/He II and C III/C IV ratios were found to vary much more slowly with temperature than the C II/C III ratio in the regime occupied by our targets. Owing to the weakness of the C IV transitions, especially in WR 88, we gave most weight to C II/C III for determining our temperatures, using the same lines for each star. For these temperatures, we find that the C IV features in WR 92 and WR 103 at 4441 and 5471 Å are underestimated by the models, but that at 5018 Å is well fitted. The C IV classification doublet at 5802–12 Å is weak, and the latter component is overwhelmed by the 5811-Å C III line in all three stars.

The fitted models and observed spectra are compared in Figs 5–7. We show two models for each star, one having the composition and parameters in Table 2, judged to be the best fit overall and, to show the sensitivity of the computed spectrum to small changes in the parameters, another model, whose differences in parameters are noted in the captions. We see, for example, that there is little to choose between the two models ($T_\star = 40$ and 42 kK) for WR 103. These temperatures are significantly lower than the 48 kK derived by C06, which used C III 5696/C IV 5801–12 for the ionization. Both these lines are too weak in the current model (Fig 7), but we chose temperatures to get the best fits to the He I/He II and C II/C III ratios that could be used in all three stars, thus allowing a differential analysis.

Table 2. Compositions and stellar properties determined from the model fits. We adopted absolute magnitudes $M_v = -4.6$ from van der Hucht (2001) and a wind clumping value of $f = 0.1$ for all three stars.

Property (units)	WR 88	WR 92	WR 103
T_* (kK)	40	39	40
v_∞ (km s^{-1})	900	900	975
X_C (per cent)	7	30	38
X_N (per cent)	0.3	0.0	0.0
X_O (per cent)	0.4	1.5	4.0
log $L/\mathrm{L}_\odot$	5.0	5.0	4.9
Distance (kpc)	2.4	3.8	2.2
$\dot{M}(10^{-5}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1})$	1.0	1.0	1.0

We have not attempted to fine tune the luminosities to fit the flux levels in the observed spectra as the absolute calibrations are not known accurately enough to justify this, but most lines are sufficiently well isolated to allow easy comparison of the observed and modelled strengths. Some lines are poorly matched: the strong C III 4650 Å feature is observed to be about a factor of 2 stronger in all three stars than in the adopted models; the same effect was observed in the analysis of WR 103 by C06 and in the modelling of these stars by S12 – which, we recall, used a different modelling code (POWR) to that used here – so this remains a work point for future analyses.

A similar difference is seen in our modelling of the broad feature centred at 3924 Å in the spectra of WR 92 and WR 103 – but not WR 88, which used a lower carbon abundance (Table 2) – and the modelling of all three stars by S12, which used the same compositions for each.

With the temperatures derived, we fitted the carbon lines – mostly C III – to get the carbon abundances in Table 2. The carbon abundance in WR 103 is definitely higher than that in WR 92, and both significantly higher than that in WR 88, which lies near the high end of the range of carbon abundances in WN/WC stars (see below). For the nitrogen abundance in WR 88, we considered the N III doublet at 4101 Å and the N IV doublet at 7103–23 Å. The fits to the two ions supports the view that the nitrogen spectrum is formed in the same wind as the carbon spectrum. These results confirm that WR 88 is a transitional WN/WC star.

For the oxygen abundances, we considered the O II feature at 4415 Å and O III at 3760 and 5592 Å. The weaker lines of multiplet 2 of O III at 3775 and 3792 Å are overestimated by models, as is the 5592-Å line, but from comparison of the fits to the WR 92 and WR 103 spectra, we are confident that the latter has the higher oxygen abundance.

The 4089-Å Si IV line is overcomputed in our model of WR 88: it is very weak in the star (the 4816-Å Si IV line is masked by N IV, Fig. 2), but we did not attempt to adjust the abundance of silicon.

Table 3. Comparison of abundance ratios (by number) derived for the stars in this study or adopted by S12 for their grid of models.

Star	C/He	O/He	Reference
WR 88	0.16		Torres (1988)
WR 88	0.07		Eenens & Williams (1992)
WR 88	0.24	0.02	S12
WR 88	0.02	0.001	This work
WR 92	0.20		Torres (1988)
WR 92	0.24	0.02	S12
WR 92	0.14	0.005	This work
WR 103	0.25		Torres (1988)
WR 103	0.16–0.29		Smith & Hummer (1988)
WR 103	0.20	0.01	C06
WR 103	0.24	0.02	S12
WR 103	0.22	0.02	This work

4 DISCUSSION

4.1 Comparison with other analyses

The WC9 stars have been the subjects of fewer abundance analyses than WC stars of earlier subtype, partly because the diagnostic C and He lines are weaker but mostly because of the greater complexity of the model atoms required. Early analyses used recombination lines in the optical (Torres 1988) or IR (Smith & Hummer 1988; Eenens & Williams 1992). The IR lines arise from high-*n* levels where non-LTE effects are believed to be less severe, and the analysis by Eenens & Williams made allowance for the ionization stratification in the stellar wind. The results, expressed as ratios of C/He and O/He (where determined) by number are compared in Table 3, noting that the values quoted from S12 are those for their grid of models – their study did not set out to determine detailed chemical compositions of individual program stars.

Omitting the ‘grid’ abundance ratios adopted by S12, the abundances ratios derived for each of the three stars in the different analyses are rather similar, with the recombination analyses tending to overestimate the C/He and O/He ratios.

4.2 The transitional WN/WC stars

As noted in the introduction, the WC spectral subtypes of the previously observed WN/WC stars are mostly very early; the 5696-Å C III classification line can be seen to be particularly weak in WR 26 and WR 58 (S12, figs B.9 and B.20). To these should be added the WN4/CE star WR 7a, whose spectrum (Pereira et al. 1998, there designated SPH2) resembles those of WR 58 and WR 145 (S12, figs B.20 and B.53) in also showing strong C IV at 5808 Å – but weak or absent 4441- and 5471-Å C IV lines. In Table 4, we list the Galactic transitional WN/WC stars whose spectra have been analysed, giving their carbon abundances.

Inspection of the C IV 5471 Å/He II 5412 Å ratios in S12’s model fits to their spectra of WR 26 and WR 126 (figs B.9 and B.46) suggests that their carbon abundances are too high; both stars deserve better data and fresh analyses. The carbon abundances found by S12 and Crowther et al. (1995b) for WR 8 are very close but those for WR 145 differ, and we prefer S12’s value because their line-blanketed models give better temperatures.

We have included the GC sources IRS 7SW and IRS 15SW in Table 4 although we are not convinced that the presence of the 2.25-μm N III lines in these stars is indicative of a WN8 spectrum because lines at the same wavelength are seen in the spectra of the WC9d stars WR 119 and WR 121. Comparison of the *H*- and *K*-band spectra of IRS 7SW and IRS 15SW generously provided by Fabrice Martins with those of WR 116 (WN8) and WR 121 shows that, with the exception of a He I line[2] at 2.15 μm, all the lines observed in the spectra of the WN8 star and IRS 7SW and IRS 15SW are also present in the spectra of the WC9 stars. This implies that it will not be possible to identify WN8/C9 stars from their *H*- and *K*-band spectra. Both the GC stars have well-developed He I spectra and low carbon abundances comparable to those of the transitional stars (Table 4), suggesting that they are in transition to fully developed WC9 stars – but we cannot classify them as WN8/C9 stars.

Evidently, the distribution amongst WN/WC stars by spectral subtype is heavily skewed to the WCE subtypes in comparison with that of the WC stars themselves, presumed to be the end products of the transitional WN/WC stars. This is shown in Table 5, where the WC population numbers are taken from Rosslowe & Crowther (2015, table 11). To get a complete sample of the known transitional WN/WC stars, we have included WR 7a and WR 153 in Table 5 but not the massive binary WR 20a (Rauw et al. 2005) recently classified as O3If*/WN6+O3If*/WN6 by Crowther & Walborn (2011) or the V Sge system WR 48c = WX Cen (Oliveira & Steiner 2004), listed as transitional WN/WC stars in the VIIth (van der Hucht 2001) and VIIIth[3] (Rosslowe & Crowther 2015) WR catalogues.

Certainly, there are selection effects hindering identification of WN/WCL stars: their location in the Galactic plane, mostly in the Inner Galaxy, makes them liable to heavy reddening. Although the *H*- and *K*-regions are unpromising for the search for WN8/C9 stars, it might be possible to identify them at shorter IR wavelengths – or from observations of the N IV lines at 7103–23 Å, where extinction is not too severe. There might be a few undetected WN/WC systems – WR 88 was known for over 40 yr before its WN/WC nature was recognized – and the spectra of unrepresented types WN/C8 and WN/C6, in particular, should be searched for N lines where they are not masked by WC emission features.

Membership of a binary system does not appear to have any influence on the occurrence of the WN/WC state. At least two of the stars in Table 4 are binaries. Gamen & Niemela (2002) showed that the C III and N IV emission lines in WR 98 moved in phase, confirming their formation in the same wind, while the Balmer absorption lines moved in antiphase, showing the presence of an OB companion. Massey & Grove (1989) showed that the C IV and N IV lines in WR 145 moved in phase in its orbit, confirming their formation in the same wind. More recently, Muntean et al. (2009) refined the orbit of WR 145, classifying the companion as O7((f)) and deriving the orbital inclination and hence masses of the components. The status of WR 8 is not as clear. Niemela (1991) found that the C IV 4441-Å and N V 4603-Å lines moved in antiphase, albeit with considerable scatter on the radial velocity (RV) curves, indicating their formation in two different stars. On the other hand, Willis & Stickland (1990) had concluded that the C and N lines were formed in the same wind and Crowther et al. (1995b) were able to model the spectrum in detail, again consistent with its formation in a single wind, indicating WR 8 to be a transitional WN/WC star. Clearly, the RVs of the lines in this star need further study to determine whether WR 8 is a WN+WC binary or a WN/WC transitional star, possibly in orbit with another star. Amongst the transitional WN/WC stars whose C abundance has not been determined, the A-component of

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[2] We discount identification with the N V line at this position because of the absence of this ion from WN8 spectra.

[3] http://pacrowther.staff.shef.ac.uk/WRcat/index.php

Table 4. Comparison of the carbon abundances (per cent mass fraction, X_C, with references) of Galactic transitional WN/WC stars together with the GC sources WR 101dc and WR 101h is discussed in the text.

WR	HD/Name	Spectral type	X_C (Ref.)
8	62910	WN7o/CE	6.0 (Crowther, Smith & Willis 1995b); 5.5 (S12)
26	MS 1	WN7b/CE	(20)(S12)
58	LSS 3162	WN4b/CE	0.1 (S12)
88	Thé 1	WN8/WC9	7 (this work)
98	318016	WN8o/C7+OB	5 (S12)
126	ST 2	WC5/WN	(20) (S12)
145	AS 422	WN7o/CE+O7V((f))	3 (Crowther et al. 1995b); 0.5 (S12)
101dc	IRS 7SW	WC9	1.5 (Martins et al. 2007)
101h	IRS 15SW	WC9	3.8 (Martins et al. 2007)

Table 5. Comparison of numbers of transitional WN/WC stars having WCE (WC4–6) and WCL (WC7–9) subtypes, compared with the Galactic WC star population, total and broken down by location following Rosslowe & Crowther.

Type/location	WCE	WCL
Transitional WN/WC	7	2
Total WC population	34	87
Inner Galaxy	5	60
Mid-Galaxy	23	23
WC Outer Galaxy	6	4

WR 153 is a WN6o/CE+O3–6 binary (Demers et al. 2002). The fraction of binaries amongst the WN/WC systems, 3–4 out of 9–11, is in line with that (39 per cent; van der Hucht 2001) for WR stars in the solar neighbourhood.

Despite the selection effects hindering discovery of WN/WCL stars, the distribution of the transitional WN/WC stars by WC subtype appears to favour the WCE stars, suggesting that these stars have more extended zones of mixed CNO-cycled and He-burned material. A better knowledge of the incidence of the transitional stars, including searching for more transitional WN/WC stars amongst the unrepresented subtypes WC6 and WC8, would provide valuable input for evolutionary modelling.

4.3 Carbon, oxygen and dust formation

Confirmation that the differences in the O II lines between WR 92 and WR 103 can be ascribed to a difference in oxygen abundance implies that similar abundance differences pertain to the other WC9 stars studied in Paper I: that two of the dust-free WC9 stars (WR 81 and WR 92) which have lower abundances of oxygen than the eight dust-making WC9 stars observed. This raises two questions. First, is this apparent correlation between oxygen abundance and dust formation observed in the larger population of WC9 stars now known? And, secondly, is the higher abundance of oxygen in some or all dust-making WC9 stars *necessary* for dust formation, e.g. for the formation of CO along the condensation pathway, or is it just an accompaniment to higher carbon abundances, as is the case of WR 103 versus WR 92, indicating more advanced chemical evolution and favouring dust formation? As to WR 88, it is likely that its much lower carbon abundance accounts for its not making dust, and the presence of nitrogen in its spectrum shows it to be much less evolved than the other two stars.

To answer the first question, we need spectroscopy of more dust-free WC9 stars to measure their O II–III lines for comparison with those in the dust-makers. Recently, many more dust-free WC9 stars have been discovered but most, especially those found in the IR surveys (e.g. Shara et al. 2012), suffer heavy reddening, making extension of the search for differences in oxygen abundance based on spectroscopy of the O II-III lines in the blue difficult. More accessible observationally are the WC9 stars found in optical surveys (e.g. Shara et al. 1999; Hopewell et al. 2005), and priority should be given to extending the small number of dust-free WC9 stars studied spectroscopically to include the oxygen lines. Suitable candidates are WR 75a, WR 75b and WR 75c, which were shown to be dust-free by Hopewell et al. (2005) on the basis of their optical-IR colours. The IR data came from the 2MASS survey (Skrutskie et al. 2006), which provided ‘snapshots’ of the IR emission (in mid-1999) and cannot rule out cases of episodic dust makers which can show dust-free spectral energy distributions for long periods between episodes of dust formation (e.g. WR 125; Williams et al. 1992). In the absence of long photometric histories like those of WR 81, WR 88 and WR 92, we can use observations in other surveys to examine the dust-free status of the candidates. They were also observed in the DENIS *iJKs* survey (Epchtein et al. 1999), generally a year before the 2MASS observations, and the *J* and *Ks* magnitudes of WR 75a, WR 75b and WR 75c in the two surveys agree to within 0.05 mag. These stars have also been observed in one or both of the *Spitzer* GLIMPSE (Benjamin et al. 2003; Churchwell et al. 2009) and *WISE* (Wright et al. 2010) mid-IR surveys. The GLIMPSE [3.6] and *WISE* *W*1 (3.4-μm) magnitudes of WR 75a agree within 0.01 mag., supporting the view that the IR flux from this star is constant. On this basis, we form near-mid-IR (non-contemporaneous) colours, $(Ks - [3.6])_0$ and $(Ks - W1)_0$, which are very sensitive to ∼1000-K dust emission but reasonably insensitive to uncertainties in interstellar reddening, and observe $(Ks - [3.6])_0 \simeq (Ks - W1)_0 = 0.36$. These are close to the corresponding colours for WR 81, 88 and 92: 0.18, 0.24 and 0.42, respectively, and less than that ($(Ks - W1)_0 \simeq 0.96$) for the light dust-maker WR 103. We do not have repeat mid-IR observations examine the variability of WR 75b and WR 75c but their non-contemporaneous colours, $(Ks - [3.6])_0 = 0.23$ and $(Ks - W1)_0 = 0.29$, respectively, support their candidacy as non-varying dust-free WC9 stars worth studying for their oxygen abundances – although these comparisons do not rule out the possibility that any of these candidates could be a long-period episodic dust-maker. The 2MASS and DENIS *Ks* magnitudes of WR 75d, the fourth dust-free WC9 star discussed by Hopewell et al., differ by 0.12 mag., and the [3.6] and *W*1 magnitudes by almost 0.26 mag., suggesting low level variability in the

IR. Also, Hopewell et al. pointed to the weaker 6570-Å emission blend in its spectrum, which they considered suggestive of binarity, so this could be a CWB worth studying in its own right.

Follow-up tailored analyses of some of the dust-making and dust-free WC9 stars, at least WR 81 if other dust-free WC9 stars were not found to have weak O II-III lines, would help answer the second question above by revealing whether the dust-makers had higher O and C abundances. The role of oxygen itself in the dust formation process through the formation of CO is uncertain and could be inimical through the reaction $O + C_2 \rightarrow C + CO$ (Cherchneff et al. 2000), attacking formation of the simplest carbon molecule. Even if CO did form, and take up some carbon atoms in what is a stable molecule, the high ratio of carbon to oxygen in WC stars evidently ensures that there is enough carbon left to form dust. There is no observational evidence for CO in WC9 spectra – examination of mid-IR spectra of WR 104, WR 112 and WR 118 (Williams, van der Hucht & Morris 1998) shows no evidence for the fundamental vibration–rotation band at 4.6 μm.

A smaller proportion of the WC8 stars also show evidence for dust formation (Williams et al. 1987), and a comparative analysis of dust-making and dust-free WC8 stars might show similar differences in C and O abundances. Although the fact that S12 were able to use the same He:C:O abundances for most of the stars they analysed suggests that there is no great spread of compositions amongst the WC stars, differential analyses of samples of WC stars would be valuable to search for differences in C and O abundance which might be ascribed to evolutionary effects.

5 CONCLUSIONS

Our detailed examination of the spectra of three WC9 stars confirms that WR 88 is a transitional WN8/WC9 star. We note the very uneven distribution by WC subtype amongst the WN/WC stars and suggest that a contributing factor is the Galactic metallicity gradient – but this cannot be the only cause. We confirm that the dust-making WC9 star WR 103 has a higher oxygen abundance than the dust-free WR 92, as suggested by its stronger O II and O III lines noted in Paper I, implying that similar spectroscopic differences amongst other WC9 stars have the same cause. The carbon abundance in WR 103 was also found to be greater than that in WR 92, and we suggest that this is the factor that allows it to form dust rather than the oxygen itself. Analysis of more WC9 stellar spectra is needed to test this conclusion.

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REFERENCES

Benjamin R. A. et al., 2003, PASP, 111, 953
Cherchneff I., Le Teuff Y. H., Williams P. M., Tielens A. G. G. M., 2000, A&A, 357, 572
Churchwell E. et al., 2009, PASP, 121, 213
Conti P. S., Massey P., 1989, ApJ, 337, 251
Crowther P. A., 2007, ARA&A, 45, 177
Crowther P. A., Walborn N. R., 2011, MNRAS, 416, 1311
Crowther P. A., Hillier D. J., Smith L. J., 1995a, A&A, 293, 172
Crowther P. A., Smith L. J., Willis A., 1995b, A&A, 304, 269
Crowther P. A., Morris P. W., Smith J. D., 2006, ApJ, 636, 1033 (C06)
Demers H., Moffat A. F. J., Marchenko S. V., Gayley K. G., Morel T., 2002, ApJ, 577, 409
Eenens P. R. J., Corral L. J., 2003, in van der Hucht K. A., Herrero A., Esteban C., eds, Proc. IAU Symp. 212, A Massive Stars Odyssey, from Main Sequence to Supernova. Astron. Soc. Pac., San Francisco, p. 174
Eenens P. R. J., Williams P. M., 1992, MNRAS, 255, 227
Eenens P. R. J., Williams P. M., Wade R., 1991, MNRAS, 252, 300
Epchtein N. et al., 1999, A&A, 349, 236
Gamen R. C., Niemela V. S., 2002, New Astron., 7, 511
Gräfener G., Koesterke L., Hamann W.-R., 2002, A&A, 387, 244
Hamann W.-R., Koesterke L., 1998, A&A, 333, 251
Harries T. J., Monnier J. D., Symington N. H., Kurosawa R., 2004, MNRAS, 350, 565
Herald J. E., Hillier D. J., Schulte-Ladbeck R. E., 2001, ApJ, 548, 932
Hillier D. J., Miller D. L., 1998, ApJ, 496, 407
Hopewell E. C. et al., 2005, MNRAS, 363, 857
Martins F., Genzel R., Hillier D. J., Eisenhauer F., Paumard T., Gillessen S., Ott T., Trippe S., 2007, A&A, 468, 233
Massey P., Grove K., 1989, ApJ, 344, 870
Mauerhan J. C., van Dyk S. D., Morris P. W., 2009, PASP, 121, 591
Moore C. E., 1959, NBS Technical Note 36, A Multiplet Table of Astrophysical Interest (Revised Edition). U.S. Department of Commerce, Washington, DC
Moore C. E., Gallagher J. W., 1993, Tables of Spectra of Hydrogen, Carbon, Nitrogen and Oxygen Atoms and Ions, CRC Press, Boca Raton
Muntean V., Moffat A. F. J., Chené A. N., De La Chevrotière A., 2009, MNRAS, 399, 1977
Negueruela I., Clark J. S., 2005, A&A, 436, 541
Niemela V. S., 1991, in van der Hucht K. A., Hidayat B., eds, Proc. IAU Symp. 143, Wolf-Rayet Stars and Interrelations with Other Massive Stars in Galaxies. Kluwer, Dordrecht, p. 201
Oliveira A. S., Steiner J. E., 2004, MNRAS, 351, 685
Paumard T. et al., 2006, ApJ, 643, 1011
Pereira C. B., Machado M. A. D., Landaberry S. J. C., da Conceção F., 1998, A&A, 338, L91
Perren G., Vázquez R. A., Carraro G., 2012, A&A, 548, A125
Rauw G. et al., 2005, A&A, 420, L9
Rosslowe C. K., Crowther P. A., 2015, MNRAS, 447, 2322
Sander A., Hamann W.-R., Todt H., 2012, A&A, 140, A144 (S12)
Shara M. M., Moffat A. F. J., Smith L. F., Niemela V. S., Potter M., Lamontagne R., 1999, AJ, 118, 390
Shara M. M., Faherty J. K., Zurek D., Moffat A. F. J., Gerke J., Doyon R., Artigau E., Drissen L., 2012, AJ, 143, 149
Skrutskie M. F. et al., 2006, AJ, 131, 1163
Smith L. F., 1968a, MNRAS, 138, 109
Smith L. F., 1968b, MNRAS, 140, 409
Smith L. F., Aller L. H., 1971, ApJ, 164, 275
Smith L. F., Hummer D. G., 1988, MNRAS, 230, 511
Torres A. V., 1988, ApJ, 325, 759
Torres A. V., Conti P. S., 1984, ApJ, 280, 181
Torres A. V., Massey P., 1987, ApJS, 65, 459
Torres-Dodgen A. V., Massey P., 1988, AJ, 96, 1076

Tuthill P. G., Monnier J. D., Danchi W. C., 1999, Nature, 398, 486
Usov V. V., 1991, MNRAS, 252, 49
van der Hucht K. A., 2001, New Astron. Rev., 45, 135
van der Hucht K. A., 2006, A&A, 458, 453
van Hoof P., Available at: http://www.pa.uky.edu/~peter/atomic/index.html
Williams P. M., van der Hucht K. A., 2000, MNRAS, 314, 23 (Paper I)
Williams P. M., van der Hucht K. A., Thé P. S., 1987, A&A, 182, 91.
Williams P. M., van der Hucht K. A., Pollock A. M. T., Florkowski D. R., van der Woerd H., Wamstecker W. M., 1990, MNRAS, 243, 662
Williams P. M., van der Hucht K. A., Bouchet P., Spoelstra T. A. Th., Eenens P. R. J., Geballe T. R., Kidger M. R., Churchwell E., 1992, MNRAS, 258, 461
Williams P. M., van der Hucht K. A., Morris P. W., 1998, Ap&SS, 255, 169
Williams P. M., van der Hucht K. A., Rauw G., 2005, in Rauw G., Nazé Y., Blomme R., Gosset E., eds, Proc. JENAM 2005 Distant Worlds, Massive Stars and High-Energy Emission in OB Associations. Université de Liège, Liège, p. 65
Willis A. J., Stickland D. J., 1990, A&A, 232, 89
Wright E. L. et al., 2010, AJ, 140, 1868

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