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L. Norci / R. F. Viotti / V. F. Polcaro / C. Rossi
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THE EFFECT OF BINARITY AND METALLICITY IN THE SPECTRA OF WC AND WO STARS

L. Norci,[1] R. F. Viotti,[2] V. F. Polcaro,[2] and C. Rossi[3]

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RESUMEN

Se presenta el estudio estadístico de la intensidad (W_λ), la relación y el ancho de algunas bandas de emisión de estrellas WC y WO, basado en un vasto conjunto de datos espectróscopicos. Se han obtenido valores medianos para cada tipo espectral. Se evidencia que en las estrellas WO y WC4 de la Galaxia, W_λ(C IV 581 nm) resulta ser menor que en estrellas extragalácticas. A su vez, el valor de W_λ(O V 559 nm) aumenta regularmente de WCL a WCE y WO, en las estrellas galácticas como en las extragalácticas. Suponemos que la variacón de la estructura del viento estelar y de la metalicidad ambiental podrían ser la causa de las anomalías. El perfil de la banda a 465 nm evidencia, asimismo, que He II 468 nm es un componente importante en las clases WCE y WO. Se comenta también sobre las abundancias de carbono y el estado evolutivo de las estrellas WC y WO. De igual manera, se estima la relación de las intensidades del continuo OB/WR en estrellas binarias.

ABSTRACT

A statistical analysis of the main emission lines common to the WC and WO stars is made based on an extensive set of spectral data. To define the trends in equivalent width (W_λ), line ratios, and line widths, median values are derived for single-spectrum stars of different spectral class. We find that in Galactic WO and WC4 stars, W_λ(C IV 581 nm) is smaller compared to in extragalactic objects. In both Galactic and extragalactic stars, W_λ(O V 559 nm) smoothly increases towards early WC and WO stars. It is argued that differences in stellar wind structure, in combination with the ambient metallicity, may be the cause of the anomalies. Variation of the profile of the 465 nm blend indicates a substantial contribution of He II 468 nm for the WCE and WO stars. In addition, we comment on the carbon abundances in relation to the evolutionary status of these objects. We also give an estimate of the OB/WR continuum flux ratio in composite-spectrum systems.

Key Words: **BINARIES: GENERAL — GALAXIES: ABUNDANCES — MAGELLANIC CLOUDS — STARS: WOLF-RAYET**

1. INTRODUCTION

Wolf-Rayet stars (WRs) are considered to be an advanced evolutionary stage of massive stars, which experience a huge mass loss. This process peels off large parts of the external envelope and brings different products of the internal nucleosynthesis to the stellar surface in different evolutionary phases. This is reflected by the nitrogen or carbon sequences of, respectively, the WN and WC stars. A third subtype of the WRs, the WO stars, was defined by Barlow & Hummer (1982) to include a small number of stars that show very strong O VI λ381 nm emission and which had previously been classified as peculiar early-type WC stars. The O VI emission lines are also relatively common in WC stars, while they are present in only two WN stars (Van der Hucht 2001). At present the WO group includes about ten members, three of which are in our Galaxy (Sand 4 = WR 102, Sand 5 = WR 142, WR 30a). Two are in the Magellanic Clouds (Sand 1 = Sk 188, Sand 2 = Brey 93 = BAT99–123 = FD73), and a few more in other Local Group galaxies (DR 1 in IC 1613, Kingsburgh & Barlow 1995, and possibly, stars no. 2, 4, 5, and 78 in M33, Smith & Maeder 1991). WR 30a and Sk 188 are binaries with an O-type companion.

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[1] Istituto di Astrofisica Spaziale e Fisica Cosmica, CNR, Roma, Italy.

[2] Dunsink Observatory, Dublin, Ireland.

[3] Dipartimento di Fisica, Università La Sapienza, Roma, Italy.

From a stellar evolution point of view, WC stars are thought to be very evolved massive stars in an advanced helium burning stage (see, e.g., van der Hucht 2001, and references therein). Their atmospheres are rich in carbon and oxygen, and are partly deprived of helium. It is expected that stars with $M_0 > 40\ M_\odot$ will undergo a core carbon burning stage (see, e.g., Maeder 1996, and references therein). From the observational point of view, no stars in a core carbon-burning stage have been unambiguously identified to date, although the WO stars have been proposed as possible candidates (e.g., Dopita et al. 1990). The understanding of the last phases of the very high mass evolution is still incomplete, but an intuitive expectation is that the chemical composition of the atmosphere of stars in core carbon burning is dominated by C and O, while He could be very weak. The observational data on WO stars (see e.g., Polcaro et al. 1995) seem to be in accordance with this picture. A recent far-UV measurement of a WO3 star in the Large Magellanic Cloud (LMC) suggests a substantial carbon enrichment (Crowther et al. 2000). However, determinations of carbon abundances in WC stars have often led to varying results regarding a possible higher abundance of this element. In a number of cases similar carbon abundance values were found for WC and WO stars.

As to the presence of helium in the atmospheres of these stars, detailed studies of WR 102 (Polcaro et al. 1992; 1995) and WR 142 (Polcaro et al. 1997) have detected this element. The He II 468 nm line is variable, which could indicate that these stars are experiencing an instability phase. Recently the hypothesis was advanced that the spectral sequence from the WC to the WO stars is based on ionization effects in the stellar wind and not necessarily connected with changes in element abundances (Polcaro et al. 1997; Crowther et al. 1998). Polcaro et al. (1999) argued that in many respects the WO stars are more appropriately considered as extreme WC stars rather than a stellar class separate from WC. The same opinion was previously expressed e.g., by Maeder & Conti (1994).

The increasing ionization level as a function of the WC/WO subtype is reflected in the spectral classification criteria for WC and WO stars. The C III 569 nm line diminishes in strength with respect to the C IV 581 nm line until the C III line is undetectable in WO stars. Similarly, the O III, O V $\lambda\,559$ blend becomes a clear feature towards the early WC subclasses and the WO stars. Other lines used for classifying WC and WO stars are the C III, C IV, He II $\lambda\,465$ blend (WC only), and the lines O IV $\lambda\,340$, O VI $\lambda\lambda\,381$-383, O VII $\lambda\,567$, O VIII $\lambda\,607$ (all WO only) (see van der Hucht 2001). Several aspects of the WC stars were investigated by Torres, Conti, & Massey (1986). They examine line equivalent width (W_λ), line width (FWHM) and line ratios for the main classification lines, and the line width of the 465 nm feature. On the basis of equivalent width ratio diagrams these authors reclassify a number of their stars. The $\lambda\,465$ width appears to correlate well with their revised subtypes. Brownsberger & Conti (1991) comment on the substantial dispersion in strength for the lines used to classify the WC subtypes (at least among the early WC types, WC4–7), while many other carbon and oxygen lines display only moderate ranges in strength.

Little has, on the other hand, been pursued for incorporating the WO stars together with the WC stars, with a view to follow the behaviour of main emission lines that are common to both WC and WO type stars. Conti & Massey (1989) find, for Galactic and LMC WC stars, that the leading emission lines are all strong or weak together, apart from C III $\lambda\,569$. However, two Galactic WO stars that they could include in a log $W_\lambda(\lambda\,581)$ versus log $W_\lambda(\lambda\,559)$ plot are a bit out of line (their other plots invoke C III which is not detected in the WO stars); one LMC WO star, Sand 2, is, on the other hand, not anomalous in that same diagram and seems to follow the overall trend observed for the WC stars. Smith, Shara, & Moffat (1990b) present the most established quantitative WC classification, according to van der Hucht (2001), and investigate particularly log $W_\lambda(\lambda\,581/\lambda\,465)$ versus log $W_\lambda(\lambda\,581/\lambda\,569)$ diagrams. The only WO star included in their diagrams is WR30a. These plots involve, however, C III $\lambda\,569$ again generally not observed in the WO stars. Smith et al. comment that for WR 30a this measurement refers to residual flux between O V $\lambda\,559$ and C IV $\lambda\,581$, with uncertain reality. Spectral modelling of WC stars has lately been reasonably successful in reproducing observed carbon and oxygen line strengths (e.g., Hillier & Miller 1998; 1999), although notably the important O VI $\lambda\lambda\,381$, 383 doublet still presents problems.

The actual subtype is probably connected with the conditions at birth of these stars. Theoretical models (Maeder 1991) show that the initial metallicity of the environment from which the progenitor of the WR star has formed is related to the spectral type of the WC star in the sense that the lower the initial metallicity, the higher is the $(\mathrm{C}+\mathrm{O})/\mathrm{He}$ ratio at the star's surface and, therefore, the earlier is the observed spectral type. The observations have shown that regions with relatively low metallicity, such as the LMC, produce exclusively very early WC types. The majority of the LMC WC stars is in fact classified as WC4 and none is later than WC6. In the Milky Way, where we expect a range of metallicities roughly increasing towards the Galactic centre, all spectral types are indeed observed, with the early types predominantly at large galactocentric distances (Smith & Maeder 1991). This seems also to hold for the WC star distribution in M33 (Massey & Johnson 1998). Stars would emerge as WC stars at earlier and earlier types for lower values of environmental metallicity, and then keep evolving from there on to earlier spectral types with the progressive peeling-off of their outer layers. The initial mass of the stars is of course also of influence as it affects the mass loss rates during the pre-WR phase.

The effect of metallicity on the spectral type of WC stars can be masked in binary Wolf-Rayets. In that case the intensity of the emission lines is diluted by the continuum of an OB companion (Smith et al. 1996; van der Hucht 2001). Also the equivalent width ratio between emission lines that are widely spaced in wavelength should be affected by the continuum slope of the OB star. Therefore, the presence of a companion has also to be taken into account when analysing the emission lines of the WR component.

In this paper we take a new look at the main emission lines that are common to WC as well as WO-type stars, in order to describe trends in equivalent width and line width over these classes, irrespective of their use for classification purposes. As Figure 1 in Torres & Massey (1987) clearly illustrates, the most prominent emission lines that appear in the spectra of both WC and WO stars are C IV $\lambda\,581$, O III, O V $\lambda\,559$, and the C III, C IV, He II blend at 465 nm. Of these, $\lambda\,581$ and $\lambda\,559$ are used as classification lines, while the $\lambda\,465$ line width has been found to correlate with the subclass allocations for WC stars. We use consistently the spectral classifications in van der Hucht (2001), which include revisions since the work of Conti & Massey (1989) and Smith et al. (1990b) quoted above. The Van der Hucht catalogue also constitutes the most up-to-date record of binary status. Following Maeder & Conti (1994) and others, the WO stars are treated as the high-ionization extension of the WC stars. As the description of the observational data in § 2 explains, available line data in the literature have been supplemented with our own measurements from the Torres & Massey Atlas, leading notably to a greatly expanded collection of line width data. The derived trends are discussed in § 3 and conclusions follow in § 4.

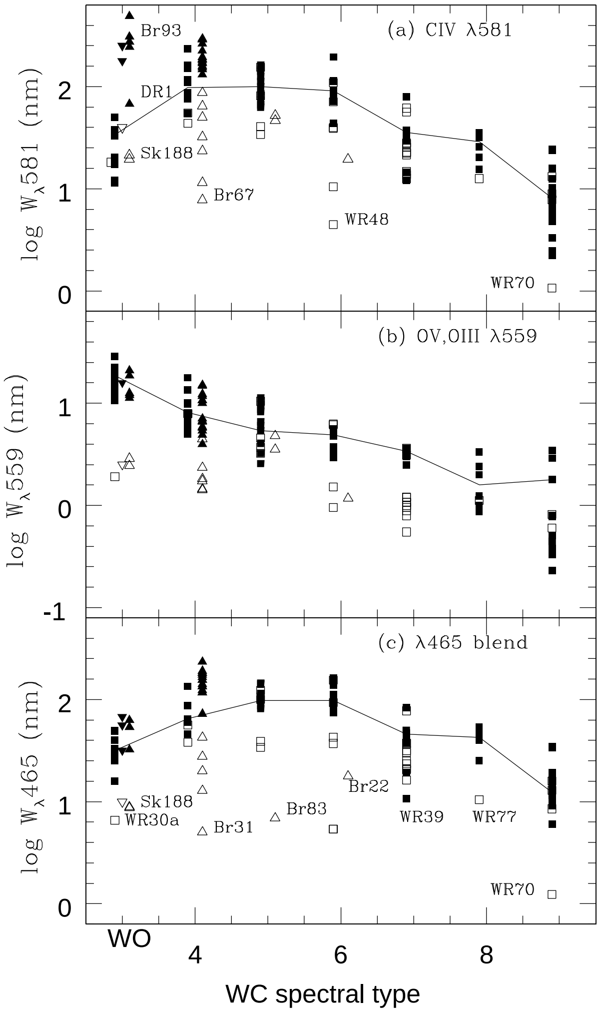

Fig. 1. Log of equivalent width for different emission lines as a function of spectral class: Galactic (*squares*) and extragalactic (*triangles*) stars are indicated. *Open symbols* refer to stars with composite spectrum. Solid lines connect median values for Galactic single-spectrum stars. *Inverted triangles* mark M33 stars. For purpose of clarity, the Galactic and extragalactic stars are slightly displaced horizontally with respect to each other.

2. DATA ANALYSIS

2.1. *The Data Sets*

For the selection of the sample of WC and WO stars we have adopted the spectral types given in the Seventh Galactic Wolf-Rayet Star Catalogue of van der Hucht (2001) and the Fourth Catalogue of Population I Wolf-Rayet Stars in the Large Magellanic Cloud of Breysacher et al. (1999). We have chosen to study the three main spectral features, which are observed throughout the whole WC class and in the

TABLE 1

EMISSION LINE MEDIAN VALUES IN SINGLE SPECTRUM WC AND WO STARS

	$\log(W_\lambda/\text{Å})$			$\log(W_{\lambda_1}/W_{\lambda_2})$		FWHM (Å)		
Subtype	$\lambda\,581$	$\lambda\,559$	$\lambda\,465$	$\lambda\,581/\lambda\,559$	$\lambda\,581/\lambda\,465$	$\lambda\,581$	$\lambda\,559$	$\lambda\,465$
WO Galactic	1.53 ± 0.25	1.27 ± 0.20	1.50 ± 0.15	0.23 ± 0.13	-0.11 ± 0.15	13.5 ± 1.3	15.1 ± 1.7	9.7 ± 1.1
WC4	1.99 ± 0.21	0.91 ± 0.19	1.81 ± 0.17	1.09 ± 0.11	0.10 ± 0.07	5.8 ± 0.7	5.8 ± 0.6	7.2 ± 0.6
WC5	2.00 ± 0.14	0.73 ± 0.19	1.99 ± 0.09	1.22 ± 0.15	-0.05 ± 0.07	4.5 ± 0.9	5.5 ± 0.8	5.3 ± 1.0
WC6	1.96 ± 0.14	0.69 ± 0.15	1.99 ± 0.11	1.35 ± 0.15	-0.01 ± 0.12	4.8 ± 1.5	4.7 ± 1.3	4.5 ± 1.2
WC7	1.55 ± 0.23	0.53 ± 0.07	1.66 ± 0.28	1.05 ± 0.13	-0.11 ± 0.07	4.6 ± 1.5	4.9 ± 0.7	4.6 ± 1.3
WC8	1.46 ± 0.14	0.20 ± 0.17	1.63 ± 0.13	1.12 ± 0.15	-0.18 ± 0.05	3.0 ± 0.7	3.0 ± 0.7	2.6 ± 0.7
WC9	0.91 ± 0.22	0.25 ± 0.27	1.09 ± 0.19	0.92 ± 0.18	-0.17 ± 0.12	3.2 ± 0.3	···	2.0 ± 0.5
WC4 LMC	2.27 ± 0.11	0.85 ± 0.17	2.19 ± 0.09	1.40 ± 0.16	0.10 ± 0.10	6.5 ± 1.1	5.7 ± 0.7	7.4 ± 0.7

WO stars, namely: the O V doublet at 558–560 nm with a contribution of O III 559 nm, the C IV doublet at 581 nm, and the 465 nm feature which is a blend of He II 469 nm, C IV 466 nm, and C III 465 nm. The O III , O V $\lambda\,559$ and C IV $\lambda\,581$ lines are normally used for the classification of these stars. Other features which are also used for the classification of the WO (O VI $\lambda\,382$) or WC stars (C III $\lambda\,569$), have not been considered in this study because they are not observed over the complete sequence of WO and WC stars.

We have collected the line measurements of WC and WO stars available in the literature: Torres et al. (1986), Conti & Massey (1989), Smith et al. (1990a; 1990b), Kingsburgh, Barlow, & Storey (1995), and Polcaro et al. (1992; 1997). Data on the four M33 stars considered here are from Massey & Conti (1983), Smith & Maeder (1991), and Willis, Schild, & Smith (1992); see § 2.5 for details on the inclusion of the M33 stars in our study. The relevant line parameters are the equivalent width (W_λ) and full width at half maximum (FWHM) of the selected lines. Whenever feasible, we have added equivalent-width and line-width data, if these were missing for any of these lines, in order to complement the published record for the WC/WO stars, so that both these line parameters are as much as possible available for all three lines. The most frequent additions are line widths. Our measurements were carried out using the Atlas of optical spectrophotometry of Galactic and LMC WC and WO stars by Torres & Massey (1987). This Atlas provides a homogeneous set of spectra covering a broad spectral range. It includes a wide spectral sample of WC stars belonging to all the subtypes, and four of the few known WO stars as well. These spectra have been analyzed using both IRAF[4] and the CRAS code (Altamore & Rossi, 1985); the results obtained with the two codes have been compared and no significant differences have been found. Similarly, we determined as a check the same line parameters as given in the literature for some of the WC/WO stars and found generally no significant differences between our own measurements and the published results.

For the values extracted from the literature, we have on the other hand encountered differences of the order of 0.1–0.2 dex between individual measurements from different authors. In the majority of the cases this probably has to be attributed to the uncertainty in the determination of the continuum level. In some cases this is due to measurements from spectra of different quality and spectral resolution, as already noticed by Smith et al. (1990a). In at least a couple of cases, WR 142 and possibly WR 102, different measured values can be attributed to intrinsic spectral variability (cf. Polcaro et al. 1997). However, at least for a statistical approach like that of the present study, these differences can be neglected with respect to the standard errors discussed below.

In total, we use data for 85 individual stars from a total of 145 measured spectra. These include 59 Galactic WC stars (91 spectra), 16 WC stars in the LMC (26 spectra), 6 WO stars (18 spectra) and 4 WR stars in M33 (10 spectra).

2.2. *Equivalent Width Sequences*

We have first investigated the change of the emission line equivalent width (W_λ) as a function of the spectral subtype. In Fig. 1 we have plotted the logarithm of the W_λ's of the selected lines as a function of the spectral subtype. The WO stars are placed next to the WC4 stars, on the basis of the higher

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[4] IRAF is distributed by the National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

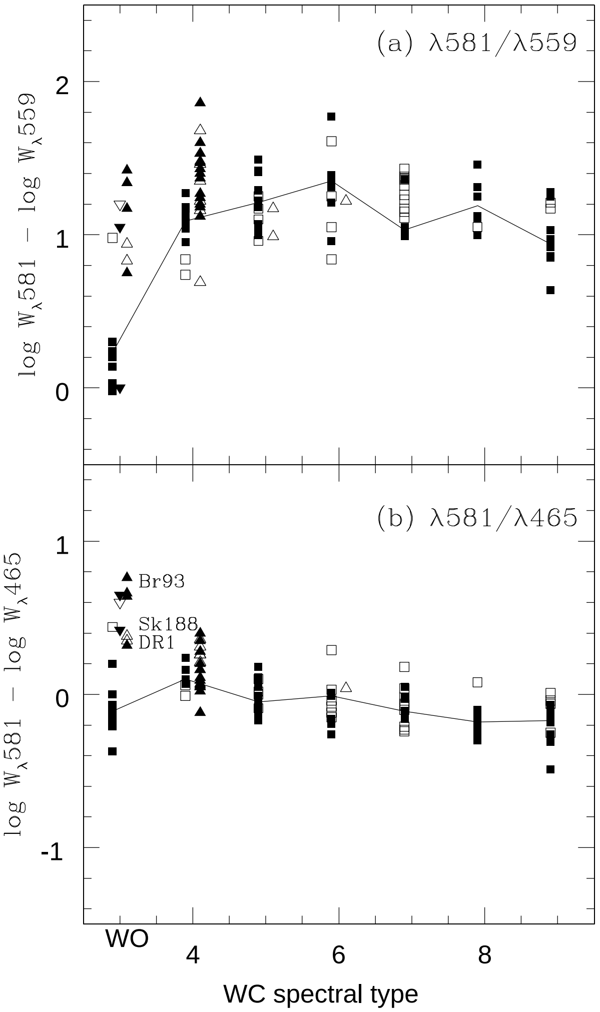

Fig. 2. Log of equivalent width ratios as a function of spectral class. Same symbols as in Figure 1.

ionization degree observed in their spectra. We assign different symbols for Galactic and extragalactic stars (respectively squares and triangles), and for single- and composite-spectrum stars (respectively, filled and open symbols). In a few cases a star is represented more than one time in the plot, when different independent measurements are available. For purposes of clarity, in the figures the Galactic and extragalactic stars are slightly displaced horizontally with respect to each other.

In Fig. 1*a* is shown the logarithm of the equivalent width of the C IV 581 nm line. In this plot the individual points show a large scatter within the various subclasses, especially for WO, WC4, and WC6. However, it is immediately clear that most of the scatter is due to the recognized composite spectrum stars which are systematically placed below the single-spectrum stars. Throughout Fig. 1, extreme cases of greatly deviating objects like WR 30a (WO4+O5), Sk 188 (WO4+O7), Brey 67 (WC4+OB), WR 48 (WC6+O9.5I), and WR 70 (WC8+B0I) are indicated. If we remove the composite spectrum stars, the scatter is largely reduced, except for the WO stars. However, in the latter case the observed spread is mainly due to a marked difference in the strength of the 581 nm line between Galactic and extragalactic WO stars. A much smaller but still noticeable difference is also present between the Galactic and Large Magellanic Cloud WC4 stars, where the Galactic stars have smaller equivalent width.

In order to give a quantitative evaluation of the trend of $\log W_\lambda(\lambda\,581)$ and of the other parameters as a function of the spectral type and of the parent galaxy, we have derived for each set of data for the single-spectrum stars the median values, which are more appropriate to our case where the distribution of the data is not Gaussian. Table 1 gives the median values for each dataset. In the table the quoted uncertainties are rms deviations from the averages, and it is assumed that these rms deviations are indicative of the uncertainty of the medians.

Solid lines in the figures connect the median values for the single-spectrum Galactic stars. It turns out that the median value of $\log W_\lambda(\lambda\,581)$ is 1.98 ± 0.12 for the Galactic WC4, WC5, and WC6 stars when taken together, from which their individual class medians deviate negligibly. This is in agreement with statements in the literature about the near constancy of the line strength in the early WC stars (WC4–6; e.g., Brownsberger & Conti 1991). In the LMC WC4 stars the median value is about a factor 2 larger, although one has to bear in mind that this is based on small number statistics. The one single WO star in the LMC (Brey 93) is even a factor 8.7 above the median of the Galactic WO stars, much more than the associated uncertainties.

This shows that the C IV line is systematically stronger in the LMC in the early-type WC stars. In fact, it is evident in Fig. 1*a* that in the Milky Way stars the equivalent width of the $\lambda\,581$ line increases towards earlier subtypes until a maximum over WC6–WC4, then abruptly falls down in the three Galactic WO stars. A continuing increase in C IV line strength is apparent for the LMC WC and WO stars (and also for the M33 stars, see § 2.5), a behaviour which is similar to that of the $\lambda\,559$ line discussed below. (The line weakness in DR 1 could be explained to some extent by continuum contamination from the parent galaxy, and/or by an unrecognized binary).

In Fig. 1*b* we plot the logarithm of the equivalent width of the O V 559 nm line as a function of the spectral type (O III contributes to this line in the later WC subtypes). Also in this case the composite-spectrum stars largely deviate towards lower values, which is as expected for a weakening of the lines due to the presence of the stellar continuum of the companion star. After excluding the composite-spectrum stars, the O V graph shows a smooth increase of $\log W_\lambda$ towards the earlier spectral types. In particular, in the WC4 stars there is no systematic difference between Milky Way and LMC, with median $\log W_\lambda(\lambda\,559)$ values around 0.9 ± 0.2. For all the WO stars the O V line appears to have nearly the same strength, irrespective of the parent galaxy, with a median $\log W_\lambda(\lambda\,559)$ of 1.25, larger than that of the WC4 stars. Also, the ionization trend within the WO subtypes suggested by Barlow & Hummer (1982), and others, has disappeared.

Finally, we show in Fig. 1*c* the behaviour of the 465 nm blend. This plot, after removal of the composite-spectrum stars, is in several respects like the above C IV plot: for the Galactic stars there is a plateau of $W_\lambda(\lambda\,465)$ from WC6 to WC5, followed by a marked decrease of the equivalent width over WC4 to WO. As for the C IV line, the median value of $\log W_\lambda(\lambda\,465)$ is larger in the LMC WC4 stars (2.19 ± 0.09) than in the Galactic WC4 stars (1.81 ± 0.17). For the WO stars the difference between Galactic and extragalactic stars appears however to be much smaller than the corresponding difference in the C IV line (Fig. 1*a*), since a decrease of the line strength now also occurs for the extragalactic WO stars.

2.3. *Line Ratio Sequences*

We have analyzed in Figure 2*a* the logarithm of the $\lambda\,581/\lambda\,559$ equivalent width ratio as a function of the spectral type. In this case the presence of a composite spectrum generally widens the scatter for each spectral type, since the diluting continuum of the companion may reduce the equivalent width of each of the lines differently. For the non-composite spectrum stars, the $W_\lambda(\lambda\,581)/W_\lambda(\lambda\,559)$ ratio is nearly constant from WC8 to WC5, with a mean value of 17. The ratio is about 12 in the Galactic WC4 stars, but is on average twice as large in the LMC WC4 stars. The difference between Galactic and extragalactic stars is even larger for the WO stars, for which the ratio is only 1–2 in the Galactic stars WR 102 and WR 142, and about 10 in the extragalactic ones.

The behaviour of the $\lambda\,581/\lambda\,465$ ratio is shown in Fig. 2*b*. It is important to notice the small scatter (0.1 in the logarithm) of the individual points in the different subtypes, and the ratio only slightly changing from late to early types, reaching a value of about 1.25 for both Galactic and LMC WC4 stars. The ratio changes towards lower values in Galactic WO stars while the extragalactic WO stars show higher values compared with the WC4 stars. The difference between Galactic and extragalactic WO stars is therefore in the same sense as for the $\lambda\,581/\lambda\,559$ ratio shown in Fig. 2*a*. The data in Fig. 1 indicate that it is mainly the 581 nm line that causes these effects regarding WO line ratios. Concerning the composite-spectrum stars, there is some indication in Fig. 2*b* that they are preferably placed above the general trend of the single-spectrum stars, in agreement with the expected steeper energy distribution of the companion stars.

2.4. *Line Widths*

One of the most distinguishing features of WC stars is the large line width, which is increasing towards earlier WC types, and is largest for the WO stars (e.g., Conti & Massey 1989). It is worth pointing out that the measure of the FWHM (or FWZI) in WR stars is ambiguous: often in these stars the continuum is ill-defined and the line profiles are complex. This yields results that are strongly dependent on the measurement techniques used by different observers. From this point of view, a statistical approach can, at least partly, overcome this problem, and can provide a quantitative description of the behaviour of the line width with spectral type.

For our analysis we adopted the wavelength independent quantity FWHM/λ. Figure 3 presents plots of this quantity for the three features here considered. Let us first deal with the width of the 581 nm and 559 nm lines. The general trend is about the same, displaying a slow increase for the Galactic stars from WC8–9 to WC4, and a conspicuous line widening for the WO stars. (Here, it is worth noting the good agreement between the median values, given in Table 1, of the velocity widths of the two emission features for each spectral type. This also confirms our averaging procedure to be effective). As for the relationship with the parent galaxy, the median line widths in the LMC and Galactic WC4 stars are the same within the errors (Table 1), while the extragalactic WO stars have $\lambda\,581$ and $\lambda\,559$ much narrower than in the Galactic counterparts. A different behaviour is displayed by the 465 nm line, with a gradual increase from the late WC subtypes to WO. In particular, the line is wider than $\lambda\,581$ and $\lambda\,559$ in the WC4 and WC5 types. This trend is better

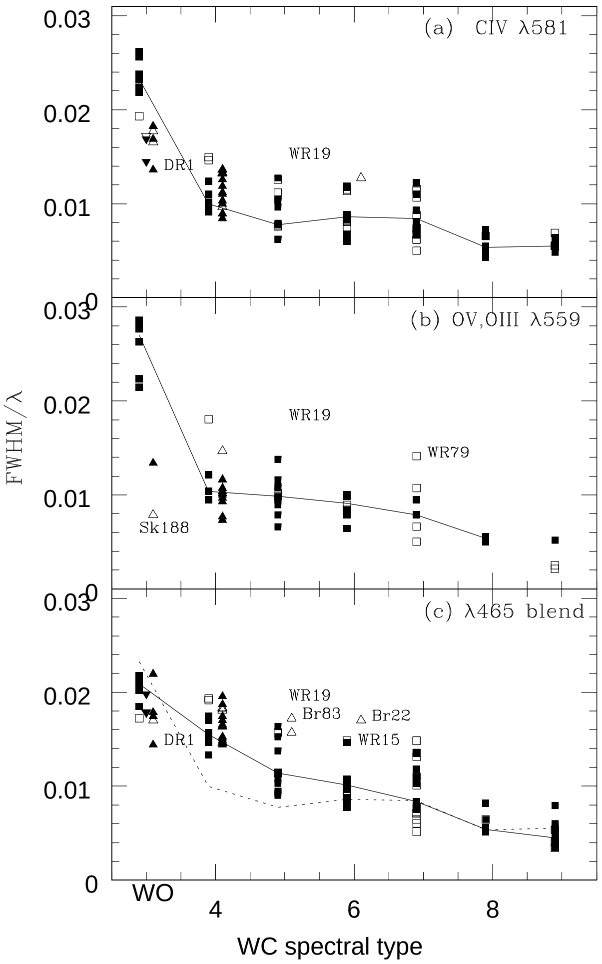

Fig. 3. Normalized line width (FWHM/λ) of the C IV 581 nm, O V 559 nm and 465 nm features as a function of the WC spectral subclass. Same symbols as in Fig. 1. Notice the dramatic width increase of the 581 nm and 559 nm lines in the Galactic WO stars, while the trend is more gradual in the 465 nm line. In this latter plot we show for comparison the median values for the C IV 581 nm line (dotted line).

illustrated by the comparison of the median values of the FWHM/λ quantities for λ 465 and λ 581 (solid and dotted lines in Fig. 3*c*, respectively), which indicates that for the WC4–WC6 subtypes the line width is enlarged due to a factor different from the velocity broadening, which could be the blending with the He II 468.6 nm line, as discussed below.

2.5. *M33 Stars*

For the sake of completeness, we have included in the plots of Figures 1 to 3 four WO stars (MC 2, 4, 6, and 78) identified by Smith & Maeder (1991) in the M33 galaxy. These stars are placed about 3–4 kpc from the M33 centre (Massey & Johnson, 1998), where the metallicity is thought to be low. Although their spectral classification is a matter of discussion (e.g., Willis et al. 1992), these stars certainly are early-type carbon/oxygen-rich WR stars. In Fig. 1*a* and 1*b* the equivalent widths of the C IV and O V lines in these stars are somewhat larger than those of the Galactic WC4 stars, in agreement with the trend of the LMC WO stars. Also the C IV line width seems to follow the behaviour of the extragalactic WO stars (Fig. 3*a*). The only exception is MC 6 (open symbol in the figures), but its line strength is probably diluted by the additional continuum of a nearby star.

3. DISCUSSION

3.1. *The Spread within Spectral Subtypes and the Binarity Effect*

From our plots, a significant spread in both W_λ and line width is observed within each spectral subtype. This was already observed by Conti & Massey (1989) who also noted that stars with composite spectra have systematically lower W_λ. Using the updated spectral type assessment in van der Hucht (2001), we have tried to determine the contribution of composite-spectrum stars to this spread.

An inspection of Fig. 1 illustrates the consistently smaller emission line W_λ of composite-spectrum stars compared to single stars of the same spectral class. Other discussions in the literature of this fact include Smith et al. (1996), Vacca, Garmany, & Shull (1996), and van der Hucht (2001). The W_λ decrease is caused by the presence of an additional continuum from the companion star or, for stars in crowded fields, by blending with the spectrum of a star close-by (Beals 1944; Brownsberger 1995; Cherepaschuk et al. 1995). The stellar companion usually is a luminous O or B star, whose luminosity may in the visual greatly exceed that of the WR star.

We have therefore in § 2 calculated the medians of the W_λ for each spectral class using only single-spectrum stars. We have then assumed that this is an estimate of the standard values of uncontaminated line strength. Once the composite-spectrum objects are ignored, the data scatter reduces to a value that should represent intrinsic variation within the spectral subclass, although measurement errors or incorrect spectral classification could in principle contribute to the observed scatter. Of course, a component of the residual scatter may be composite-spectrum stars not yet recognised as such, as may be the case of the weak-lined star WR 39 (see Fig. 1*c*). These other conceivable contributions to the scatter are unlikely to be dominant effects and we shall

TABLE 2

LOG EQUIVALENT WIDTH DEFECTS AND DERIVED
OB/WR CONTINUUM FLUX RATIO IN COMPOSITE-SPECTRUM STARS

System	Spectral Type	$\lambda\,581$	$\lambda\,569$	$\lambda\,559$	$\lambda\,465$	Ratio	Error[a]
WR30a	WO4+O5	0.27	···	0.99	0.68	3:	d
Sk188	WO4+O7	···	···	0.78	0.8:	6.0	c
Brey 28	WC4+OB	0.76	···	0.69	0.89	5.0	b
Brey 31	WC4+O8I	1.21	···	0.48:	1.49	10:	d
Brey 32	WC4+O6V	0.90	···	0.70	1.08	7.0	c
Brey 44	WC4+O9	0.46	···	0.20	···	1.1	c
Brey 62	WC4+OB	0.45	···	0.60	0.63	3.0	b
WR 19	WC4+O9.5	0.15	0.15	0.01:	0.15	0.4	c
WR 9	WC5+O7	0.43	0.37	0.19	0.43	1.3	b
WR 27	WC6+abs	0.01	−0.03	−0.11	−0.09	$\ll 1$	b
WR 30	WC6+O6–8	0.37	0.36	0.71	0.36	1.3	b
WR 48	WC6+O9.5I	1.31	1.15	···	1.26	16.0	b
WR 146	WC6+O8	0.24	···	···	0.39	1.1	c
SSPM1	WC6+abs	0.94	0.59	0.51	1.26	4:	d
WR 39	WC7+?	0.53	0.44	···	0.50	2.1	a
WR 42	WC7+O7V	0.22	0.36	0.71:	0.06	1:	d
WR 79	WC7+O5-8	0.11	−0.02	0.45:	0.16	$\ll 1$	a
WR 86	WC7+B0III–I	0.41	0.23	0.50	0.45	1.5	c
WR 93	WC7+O7–9	0.12	0.15	0.45	0.18	0.4	b
WR 125	WC7+O9III	0.16	0.07	0.55	0.34	0.9	c
WR 137	WC7+O8	0.31	0.28	0.56	0.30	1.1	c
WR 140	WC7+O4–5	0.20	0.35	0.50	0.29	1.2	c
WR 77	WC8+OB	0.36	0.29	0.15	0.61	1.2	c
WR 70	WC9+BOI	0.88	1.13	···	1.54	9.0	c

[a] Logarithmic error flags: a: < 0.1, b: 0.1, c: 0.15, d: 0.2–0.3.

assume in the following that the scatter among the single star data reflects a real variation within a class.

As ror the single star scatter, it is also known that some stars show consistently weak or strong lines (Conti & Massey 1989) within a particular spectral subtype. A recent study, based on 25 WC stars of spectral types WC5–8 (Koesterke & Hamann, 1995), shows that weak-lined and strong-lined WC stars differ in effective temperature and structure of the wind. The weak-lined WC stars have $T_{\rm eff} \sim 50$ kK and continuum formation in regions with small expansion velocities, while strong-lined WCs have $T_{\rm eff} \sim 60$–100 kK and thick winds (continuum formation at high expansion velocities). Therefore, the observed spread of W_λ is likely to be intrinsic to the nature of these stars, caused by their observed spectral properties being determined by the structure of their winds, while abundance differences are another probable contributor.

It is known that the classification of WC stars, which relies on the relative strengths of lines at different ionization potentials (O V 559 nm, C III 569 nm, and C IV 581 nm), fails to relate directly to the stellar temperature or to other stellar physical parameters (Eenens, Williams, & Wade 1991). Eenens et al. suggest that the WC classification ratios are actually referring to a two-dimensional classification scheme in which two independent physical properties are addressed, such as, for example, ionization and C–O abundance. The existence of a second parameter would then determine the observed spread. However, Smith et al. (1990b) found no systematic trend of the flux of the 581 nm line within the WC4–7 subclasses.

Taking the calculated median values for non-composite spectrum stars as reference, and assuming that the observed downward deviations in stars with composite spectrum are due to the additional continuum of the OB star, we have derived the continuum flux ratio between the WR star and its companion. The results are given in Table 2, where, as a complement, the equivalent width of the C III 569 nm line was also used, assuming the measured median $W_\lambda(569)$ values of 0.58 (WC4), 0.88 (WC5), 1.05 (WC6), 1.21 (WC7), 1.65 (WC8), 1.44 (WC9). The table also includes the WC7 star WR 39 showing, according to van der Hucht's (2001) terminology, diluted emission lines that can be attributed to the strong continuum of a stellar companion. In general, our flux ratios for eight cases in common are in good agreement with the magnitude differences reported in Table 24 of van der Hucht's (2001) Catalogue. It results that the OB/WR continuum ratio could be as large as one order of magnitude higher. Since the Wolf-Rayet star is the most evolved component of the binary system, it originates from the initially most massive of the two companions. The result obtained for the continuum ratios is in agreement with the known effect of a large luminosity fading following the O-supergiant phase, due to the huge amount of matter lost by the star prior to the Wolf-Rayet stage both in single (e.g., Maeder 1999) and in binary stars (e.g., Langer & Heger 1999). We also notice that these considerations also apply to those cases in which the two stars do not form a true binary system, but are coeval nearby stars.

From Fig. 1 one can also notice that the downward shift for binaries at 465 nm is in many cases larger than for the other two lines, in agreement with the fact that in a WR+O binary system, the O component should have a steeper rising continuum towards shorter wavelengths. A more detailed investigation with high quality spectroscopic data is necessary to determine more accurately the modalities of this phenomenon.

Concerning the line widths of the composite-spectrum stars, there is in general no systematic difference with respect to the single-spectrum stars (Fig. 3). There are, however, some individual cases, such as WR 19 and WR 79, showing a significantly larger wind velocity; a more detailed study of these will be worthwhile. Also, for composite-spectrum stars, the $\lambda\,465$ blend could be widened by the presence of an unseparated strong emission feature near 465–468 nm from an Of-type companion.

3.2. *The C IV Anomaly in Galactic WC4/WO Stars*

As discussed in § 2, environmental effects appear particularly evident in the behaviour of the strength of the C IV 581 nm line. The different trend of the strength of the C IV 581 nm line in the Galactic and extragalactic WCE/WO stars (Fig. 1*a*) culminates in the WO stars, with the Galactic WO stars having a dramatically lower W_λ than extragalactic WOs. Such an effect is absent in the O V 559 nm line (Fig. 1*b*), which shows a smooth behaviour throughout the whole WC class and into the WO stars, for both Galactic and extragalactic objects. This suggests that the decrease in C IV strength in the early-type Galactic stars is not a temperature effect. Also this cannot be explained by assuming that the Galactic WCE/WO stars are all weak-lined WR stars. If this were the case, all their lines would consistently show smaller W_λ, whereas the O V line in fact appears to be unaffected. One may imagine that the different behaviour between the two lines is due to a cause that selectively operates on C rather than on O.

The third line that we are considering in this work is the feature at $\lambda\,465$, which includes a C IV line at $\lambda\,466$ blended with C III $\lambda\,465$, and He II $\lambda\,468$; it shows also a downward bending for the Galactic WO stars, starting already in the WC4 class. C III $\lambda\,465$ cannot be expected to contribute hugely to this line in very early WC spectral types and the C IV $\lambda\,466$ line will be more important. He II $\lambda\,468$ is known to contribute to the $\lambda\,465$ nm feature as well, increasingly more blended with the C III/C IV line, and increasingly stronger with respect to C III/C IV when going from late WC types to early WC to WO. In Figure 1 of Torres & Massey (1987) the He II line is easily individually recognizable from WC9 to WC5; for WC4 and WO the lines are blended together into an overall broad feature. This point is also supported by the profile shape of the $\lambda\,465$ feature that shows the peak of the blend moving from the position of the C IV 466 nm line (WC5–6 stars) towards the position of the He II line (WO stars).

Figure 4 illustrates this for a selection of $\lambda\,465$ line profiles of WCE and WO stars. For the WC5–6 stars the $\lambda\,465$ line is peaked at the position of the C IV 466 nm line with a hump on the red side at the position of the helium line. The line becomes broader and broader with correspondingly lower peaks from WC6 to WC4. In some WC4 stars the peak of the generally flat-topped line is noticeably displaced towards the He II line. In the WO stars the line barycenter lies in between the C IV and He II lines, indicating that they may be comparable in strength. The difference in the red wing extent between the two WO stars, Brey 93 (LMC) and WR 142 (MW), may be due to differences in wind clumping, similar to what has been inferred with model analyses for WC4 stars (Gräfener, Hamman, & Hillier 1998).

The presence of He II in WO stars was contested by e.g., Dopita et al. (1990) on the grounds that these lines had not been observed outside blends, and this argument was used to suggest that WO stars might be in a core carbon burning phase. On the other hand, helium was spectroscopically identified in the wind of the Galactic WO stars WR 102 and WR 142 (see e.g., Eenens 1991; Eenens et al. 1991; Polcaro et al. 1992; 1997). Recent models calculated for early WC stars show that He II indeed contributes significantly to the 465 nm blend, as well as C IV and C III (W.-R. Hamann, private communication 2001).

If we now concentrate again on the C IV $\lambda\,581$ line that shows the drop in W_λ for (Galactic) WO stars in the most uncontaminated way, it is natural to think that this effect could be caused, directly or indirectly, by the different metal content of the parent galaxies, in view of the above discussed discrepancy between Galactic and extragalactic objects. The ambient metallicity is expected to affect the age at which stars enter the WR phase and the duration of that phase (Maeder 1991). The initial metallicity would influence the mass at which a star enters the WR phase in the sense that the higher is Z, the higher is the mass loss rate and the lower is the mass for WR formation. The theory indicates a relation between the atmospheric C + O/He ratio and spectral type, implying that stars with high initial Z will spend most of their time as late WCs.

It may be useful to examine published physical parameters for WC and WO stars in order to look for any peculiarities of the WCE/WO stars that could be related to the anomaly of C IV, possibly dependent on environment. Such data are available for 30 Galactic WC stars (Nugis & Lamers 2000) complemented by the luminosity estimates of six LMC WC stars and of the SMC WO star Brey 93 (Gräfener, Hamman, & Koesterke 1999; Crowther et al. 2000). Mass-loss rate, luminosity, wind momentum $[\dot{M}v_\infty/(L/c)]$, Z and Y seem to behave in an orderly fashion, without suggesting peculiarities for the WO stars. The temperature of the hydrostatic core and the mass at the WR stage (derived from theoretical tracks once the luminosity is known) are consequently also in line with expectation. The WO stars can in particular be seen as an extension of WCE stars as far as these parameters are concerned, an exception interestingly being the terminal wind velocity, v_∞, that exhibits an abrupt increase for the Galactic single WO stars.

This suggests that variation in physical conditions in the wind may be the cause of the observed differences between the C IV $\lambda\,581$ and O V $\lambda\,559$. The wind conditions are likely to depend on metallicity, analogously to what happens in other hot stars (Kudritzki & Puls 2000), although in WR stars it is not yet proven that the momentum transport by photon scattering (single or multiple) is solely responsible for the observed wind acceleration (Hillier & Miller 1999). The WR stars form lines with different ionization degree at different depths in the stellar wind, which seems to be the key to understanding their winds (Lucy & Abbott 1993; see also Schulte-Ladbeck, Eenens, & Davis 1995). In particular the Galactic WO stars WR 102 and WR 142 display a large velocity gradient as a function of the parent ion (Polcaro et al. 1997; their Figure 3).

There is evidence for peculiar WC stars for which the line ratios adopted for classification (which include C IV $\lambda\,581$) are self-contradictory, in the sense that the two classification ratios lead to two different spectral subtypes. This happens for one out of four WC4–7 stars and the situation is even worse at later types (Torres et al. 1986; Smith et al. 1990b; Eenens et al. 1991). It has also been noted in the literature that peculiar excitation mechanisms may affect classification lines such as C III $\lambda\,569$ (see Eenens et al. 1991). Reionization from shocks has been invoked to explain anomalies in the profiles of C III $\lambda\,569$ and C IV $\lambda\,581$, that would imply that C IV 581 forms further out in the stellar wind than C III $\lambda\,569$ (Lépine et al. 2000). This would be in contradiction with the normally observed wind stratification that rather indicates that the lower ionization lines are formed further out in the wind. An alternative explanation is however also offered that postulates increased clumping size in the WR wind.

Whether the metallicity is actually causing the observed discrepancies between the Galactic and extragalactic WCE/WO stars in the C IV lines, via the stellar wind structure, is a matter that cannot be settled without the application of detailed spectral models, a task outside the scope of the present paper. While the spectrum of Brey 93 (the LMC WO star) has recently been fitted with such models (Crowther et al. 2000), application of the same procedure to the two Galactic WO stars is hampered by the large interstellar reddening towards these stars and by the extreme complexity of their spectra.

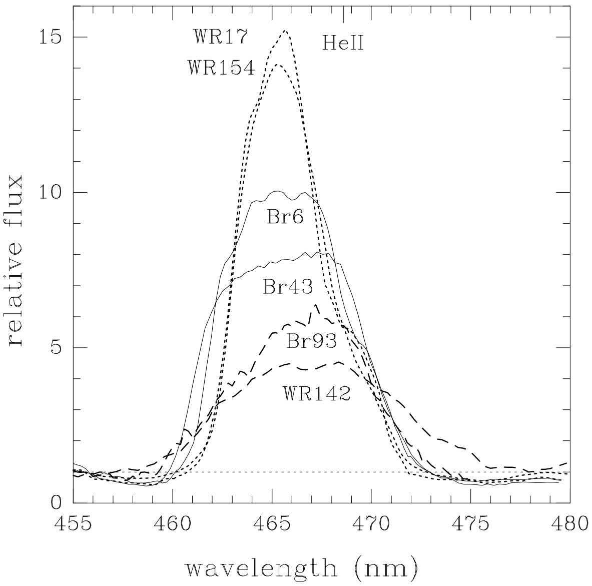

Fig. 4. The 465 nm emission line in WO and WCE stars. The stars are: WR 142 (WO), Brey 93 (WO), Brey 6 (WC4), Brey 43 (WC4), WR 17 (WC5), WR 154 (WC6). Fluxes are normalized to the continuum. A radial velocity correction (blueshift) is applied to the LMC stars.

3.3. *Carbon Abundances*

In view of the importance of carbon in the WC and WO stars in relation to the evolutionary status of these objects, we add a few comments on the inferred abundance of this element in such stars. Observations have given contrasting results as to the carbon abundance in WC stars. No clear correlation between either spectral type and carbon abundance, or between carbon abundance and stellar parameters has been established as yet.

The modelling of the spectra of the WC stars (from which abundances may be derived) is hampered by the complexity of the spectra; severe blending of the broad emission lines renders the comparison with observed spectra rather difficult. Models containing He, C, O, Si, and Fe lines have been published recently (Hillier & Miller 1998; Gräfener et al. 1998). Work of this sort has provided a quite satisfying fit for most of the He, C, O and Si lines of the WC5 star HD 165763 (Hillier & Miller 1999). A number of problems are nevertheless still present for the higher ionization O lines (such as the O VI 381–383 nm doublet), and for the Fe lines.

Hillier & Miller (1999) calculated C/He and C/O ratios for HD 165763, obtaining identical values to those derived for two Galactic and the LMC WO star Brey 93 (Kingsburgh et al. 1995) and similar values to those of 6 LMC WC4 stars (Gräfener et al. 1998) and again of Brey 93 (Gräfener et al. 1999). Crowther et al. (2000), interpreting far-UV *FUSE* spectroscopic measurements, suggest that Brey 93 would be more chemically enriched in carbon than the LMC WC stars, and therefore possibly be in a more advanced nuclear burning phase. Being a WO star in a low-metallicity environment, Brey 93 must have started off as a very massive star indeed (in order to reach the large amount of mass loss required) and therefore, could be in a more advanced evolutionary stage than the Galactic WO stars. It will be interesting to see whether the Galactic WO stars, that originate from a higher metallicity environment, are less evolved or allow a similar conclusion regarding carbon enrichment as for this LMC WO star.

4. SUMMARY AND CONCLUSION

We have collected an extensive set of spectral data on the basis of up-to-date spectral type and binarity information (as in van der Hucht 2001; Breysacher et al. 1999) and have examined trends in W_λ and line width over the WC and WO classes. We concentrate on the main emission lines common to the WC and WO classes: the O V doublet at 559 nm, the C IV doublet at 581 nm and the 465 nm feature. In those cases where values of W_λ or line width were missing, these have been measured, whenever possible, from the Torres & Massey (1986) Atlas. We assume for the purpose of this investigation that the WO stars are an extension at high ionization of the WC stars.

Contributions of composite-spectrum stars to the observed spread in W_λ within spectral classes have been avoided as much as possible, and the median W_λ values of chiefly single stars has been adopted as an estimate of the standard values of the uncontaminated line strength. The residual spread is judged to be mainly due to intrinsic variation of W_λ within a spectral class. This is an indication that W_λ depend on more than one parameter. Generally, the binary or composite-spectrum stars exhibit smaller values of W_λ due to dilution from the additional continuum flux of the OB companion. An estimate is given of the OB/WR continuum flux ratio in many composite-sprectrum systems.

The C IV 581 nm line W_λ shows an increasing trend from late to early WC types and to WO stars. A difference emerges between Galactic and extragalactic stars in the WC4 and WO classes with the Galactic W_λ being significantly smaller than the extragalactic ones. The effect is particularly evident in the WO spectral class. Such an effect is, on the other hand, absent in the O V 559 nm line, where the W_λ increases smoothly from late to early WC types, showing similar behaviour for Galactic and extragalactic stars. The W_λ of the 465 nm feature does decrease over WC4 and WO as for the Galactic C IV 581 nm W_λ although not to the same extent.

The line widths of C IV 581 nm and O V 559 nm show a marked increase for the Galactic WO stars. In a couple of cases (WR 9, WR 79) a significantly larger wind velocity would justify further investigation with better quality spectroscopic data; we note that these are binaries. Some cases of large line width for the 465 nm blend also concern binaries and may be due to additional features in the companion spectrum.

Since the observed differences are between stars in different environments (mainly Galaxy versus LMC), the metallicity of the parent galaxy may be decisive, as it is known that ambient metallicity affects the life and evolution of Wolf-Rayet stars. Because the difference between Galactic and extragalactic stars is particularly evident in the WO class, we have looked for any evident peculiar characteristic of the WO stars by inspecting the physical parameters of WC and WO stars extracted from the literature. The only noticeable peculiarity seems to be the extremely high wind terminal velocities of the Galactic WO stars compared both to Galactic WC4 stars and to extragalactic WO stars. We conclude that the anomalies of Galactic WO stars may originate from the properties of the wind.

Detailed spectral models will be required to investigate whether the observed (Galactic) anomalies are caused, via the wind structure, by the ambient metallicity. The fit of spectral models to a WO spectrum is complicated by the blended nature of many of the broad lines; it requires the modelling of the oxygen lines and has to take into account the effects of line blanketing that are so important in these very dense winds. One such model applied to a extragalactic WO star (Brey 93) seems to indicate a higher carbon abundance, which is interpreted as sign of a very advanced evolutionary stage. The application of detailed models to the Galactic WO stars is, on the other hand, hampered by the very reddened spectra of these objects.

The dependence of the mass loss on both metallicity and initial stellar mass implies that only very massive stars can reach the WO phase in low metallicity environments. Smith & Maeder (1991) have shown that there is a relation between the spectral type of Galactic WCs and galactocentric distance. The Galactic WCE stars are usually located at large galactocentric distances, where the metallicity is lower; the low metallicity environment of the LMC contains only WCE and WO stars. Thus it is suggested that a low metallicity environment produces preferentially WCE stars. This effect has been confirmed by Willis et al. (1992) for the case of M33. On the other hand, the Galactic WO stars WR 102 and WR 142 are both located in high metallicity regions, although they are considered to be the most extreme WCE stars. It will then be interesting to investigate what the evolutionary status of the Galactic WO stars is, in comparison with their extragalactic counterparts, and whether a carbon enrichment comparable to what has been estimated for Brey 93 has taken place.

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L. Norci: Dunsink Observatory, Castleknock, Dublin 15, Ireland (ln@dunsink.dias.ie).

V. F. Polcaro and R. F. Viotti: Istituto di Astrofisica Spaziale e Fisica Cosmica, CNR, Area di Ricerca di Tor Vergata, Via del Fosso del Cavaliere 100, I-00133 Roma, Italy (uvspace@saturn.ias.rm.cnr.it).

C. Rossi: Dipartimento di Fisica, Università La Sapienza, Piazzale Aldo Moro 1, 00185 Roma, Italy (corinne.rossi@roma1.infn.it).