Colliding winds in Wolf-Rayet binaries
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The Ultraviolet Variability of WR 140

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Multi-frequency variations of the Wolf-Rayet system HD 193793 (WC7pd+O4-5).
III. IUE observations

The colliding-wind binary system WR 140 (HD 193793, WC7pd+O4-5, P=7.94 yr) was monitored in the ultraviolet by IUE from 1979 to 1994 in 35 short-wavelength and 18 long-wavelength high-resolution spectra. We report here on results of our analysis of the SW spectra of this long-period binary. An absorption-line radial-velocity solution is obtained from the photospheric absorption lines of the O component, by comparison with a single O star. The resulting orbital parameters confirm the large eccentricity of the orbit, $e_{UV} = 0.87 \pm 0.05$, within the uncertainties of previous optical studies. This brings the weighted mean UV-optical eccentricity to $e=0.85 \pm 0.04$. Occultation of the O-star light by the WC wind and the WC+O colliding-wind region results into orbital modulation of the P-Cygni profiles of the C II, C IV and Si IV resonance lines. At periastron passage, the absorption troughs of those resonance-line profiles increase abruptly in strength and width, followed by a gradual decrease. In particular, at periastron the blue black-edges of the P-Cygni absorption troughs shift to larger outflow velocities. We argue that the apparently larger wind velocity and velocity dispersion observed at periastron can be explained by three phenomena: (i) geometrical resonance-line eclipse effects being the main cause of the observed UV spectral variability, enhanced by sightline crossing of the turbulent wind-wind collision zone; (ii) possible common-envelope acceleration by the combined WC and O stellar radiation fields; and (iii) the possibility of an orbital-plane enhanced WC7 stellar wind.
3.1 Introduction

Wolf-Rayet (WR) stars are massive stars characterized by strong stellar winds, driving mass-loss rates of the order of $10^{-5} \, M_\odot \, yr^{-1}$ (viz., van der Hucht 1992). In the case of WR+OB binary systems, wind-wind collision causes heating and compression where the WR and OB wind momenta match. In case of eccentric binary orbits, the change in binary separation of, and in lines-of-sight to, the two binary components cause variability in several wavelength domains: X-ray flux variability, ultraviolet line-profile variability, infrared flux variability in case of episodic dust formation, and non-thermal radio flux variability.

WR 140 (HD 193793, V1687 Cyg, van der Hucht et al. 1981; van der Hucht 2001), is a spectroscopic WC7 binary system with a O4-5 companion (according to Arnal (2001) possibly escaped from a triple system some $1.3 \times 10^6 \, yr$ ago), for which the difficulties in finding a reliable radial-velocity solution have puzzled many observers (e.g., McDonald 1947; Conti 1971; Cherepashchuk 1976; Lamontagne et al. 1984; Conti et al. 1984). First classified as a WR star by Fleming (1889), its variability has drawn attention only since the 1970s. Discovery papers are: Schumann & Seggewiss (1975) on optical spectral variability; Hackwell et al. (1976) on infrared photometric variability; Florkowski & Gottesman (1977) on radio variability; Moffat & Shara (1986) on optical photometric variability; and Williams et al. (1987b) on its combined IR, UV and X-ray variability.

As to continuum variations, UV photometric variability in WR 140 has been looked for in ANS data by Burton et al. (1978), who found within half a year no variations larger than 1% in the five ANS UV channels. Williams et al. (1990b, hereafter Paper I) searched for UV continuum variations in the then available IUE spectra of WR 140, but found none. At optical wavelengths, Moffat & Shara (1986) found micro-variability in broadband $B$ observations of WR 140 obtained in a time span of 14 days, with an amplitude of 0.02 mag and a tentative period of $P=6.25 \, d$. More recently, Panov et al. (2000) monitored WR 140 from 1991 to 1998 in $UBV$ photometry. In 1993, a dip in the light curve in all passbands has been observed around periastron passage (see below), with a sl $V$-amplitude of 0.03 mag. They interpreted this dip in terms of an ‘eclipse’ by dust condensation in the WC wind, of the type reported by Veen et al. (1998) for a number of late WC stars.

Thanks to the development of IR photometry in the early 1970s, unexpected IR variability of WR 140 was discovered. Its IR fluxes decreased from 1970 to 1975, brightened in 1977, and, after two months at maximum, faded back to a quiescent level in about three years. This IR excess has been interpreted by Williams et al. (1978) as condensation episode of amorphous carbon dust grains. In 1985 another IR excess occurred, of $\Delta L' \simeq 2.5 \, mag$ within six weeks. The $7.94 \, yr \, (2900 \pm 10 \, d)$ interval between these two IR excesses was proven, by a radial-velocity solution, to be the orbital period of an eccentric ($e=0.84$) binary by Williams et al. (1987b); confirmed by Moffat et al. (1987); and elaborated on by Williams et al. (1990 Paper I), with the IR excesses associated with periodic dust formation during periastron passage. This motivated the classification WC7pd (van der Hucht 2001). A third IR excess of WR 140 occurred at the predicted time in March 1993 (Williams 1995; 2001). Excess IR fluxes have been observed in some 26 WC stars (most of them constant, some variable) by Williams et al. (1987a; see also Williams 1999), and are interpreted as being caused by local cooling and compression in carbon-rich WC winds with subsequent amorphous carbon dust formation. The astrochemistry of the dust-formation process in WC winds is still poorly understood (Cherchneff et al. 2000).
3.1 Introduction

Annuk (1995) measured the radial velocities of absorption lines and the C IV λ 4650 Å emission line. Combining his observational result and those of others, he derived a period of 2893 d. Annuk’s absorption-line solution confirmed the orbital elements derived in Paper I with a slightly larger eccentricity, e = 0.85 ± 0.01.

WR 140 also displays variable non-thermal radio emission, modulated by the eccentric orbital motion of the binary components (Williams et al. 1990b; 1994, hereafter Paper II; White & Becker 1995a). Non-thermal radio emission is observed from a number of other WR stars as well (e.g., Abbott et al. 1986; Leitherer et al. 1995; 1997; Chapman et al. 1999; Setia Gunawan et al. 2000; 2001a). In many cases this has been associated with binarity (WR+OB) and colliding winds. Van der Hucht et al. (1992) suggested a colliding wind binary (CWB) origin for all non-thermal radio emission from WR and OB stars. This has been corroborated by later observations, as summarized recently by Dougherty & Williams (2000b). The observed non-thermal radio emission is most likely due to synchrotron radiation from particles accelerated by shocks formed by the colliding winds (e.g., Eichler & Usov 1993).

The relatively strong X-ray emission from some WR binaries, e.g., WR 125 and WR 140 (Pollock 1995), is another indication of heating in wind-wind collision regions (Usov 1992). Recent X-ray studies of WR 140 are by Zhekov & Skinner (2000) and by Aleksandrova & Bychkov (2000).

The observations mentioned above lead to a model for WR 140 of a WC7pd+O4-5 binary with interacting stellar winds forming two shock fronts with a contact discontinuity in between (Paper I). Since the ratio of the wind momenta \( \eta = \dot{M} v_\infty (\text{WC7}) / \dot{M} v_\infty (\text{O4-5}) \approx 33 \), the cone-shaped contact discontinuity is formed relatively close to the O component, with an opening angle depending on the value of \( \eta \). Applying the orbital elements derived in Paper I, the O component is, in the line-of-sight, ‘behind’ the WC star roughly at phases 0 < \( \phi < 0.1 \) (see Fig. 3.2; periastron defines \( \phi = 0 \)). In this phase range, the sightline (assuming an inclination \( i \gtrsim 60^\circ \)) to the O component passes through the densest part of the WC and O stellar winds and their interaction region. Because in the UV the O component is \( \sim 0.7 \) mag brighter than the WC component (Paper I), absorption in the sightline to the O component will dominate the P-Cygni absorption troughs in the spectrum of the WR 140 system in this phase range. The sightline to the O component is for about half of the orbit dominated by the WC7 wind.

Both the WC7 and O4-5 binary components of WR 140 have terminal wind velocities of the order of \( v_\infty \approx 3000 \text{ km s}^{-1} \). Fitzpatrick et al. (1982) derived from the composite (WC7+O4-5) IUE-SWP 8004 spectrum of WR 140, that the C IV λλ 1548,1551 Å, Si IV λλ 1394,1403 Å and C III λ 1909 Å P-Cygni line profiles yield \( v_\infty = 3000 \pm 100 \text{ km s}^{-1} \). They also observed two narrow absorption features in the broad P-Cygni Si IV line. Since the spacing of these narrow absorption features is identical to the doublet spacing, they interpreted the narrow features as Si IV lines with a velocity of \( v \approx -2700 \text{ km s}^{-1} \). Prinja et al. (1990) argued that the black-edge velocity (\( v_{\text{black}} \)) of the saturated absorption part of P-Cygni profiles in high-resolution IUE spectra of OB and WR stars represents the terminal wind velocity, with on average \( v_{\text{black}} \approx 0.76 v_{\text{edge}} \). From the composite (WC7+O4-5) IUE-SWP 31504 spectrum of WR 140, they measured for the resonance lines the wind velocities \( v_{\text{CII}} = 1510 \text{ km s}^{-1} \), \( v_{\text{SiIV}} = 2640 \text{ km s}^{-1} \), and \( v_{\text{CIV}} = 2900 \text{ km s}^{-1} \). Eenens & Williams (1994) measured the terminal velocities of WR stars from the P-Cygni absorption components of the near-IR He I lines at λ 1.083 μm and λ 2.058 μm. They found that the observed He I terminal
wind velocities correspond to about 70% of the violet-edge velocities of the UV resonance P-Cygni profiles of C IV and Si IV, agreeing well with \( v_{\text{black}} \) of the saturated absorption troughs. The terminal wind velocities that they derived for WR 140 are \( v_{\text{HeI} 1.083 \mu m} = 2900 \text{ km s}^{-1} \) and \( v_{\text{HeI} 2.058 \mu m} = 2845 \text{ km s}^{-1} \), and are ascribed to the WC7 component.

The motivation for the present study was to monitor WR 140 for variations in the UV P-Cygni profiles of resonance lines of abundant ions as a function of orbital phase, and to obtain an UV radial velocity solution, the combination of both allowing to interpret any observed variations as a function of orbital geometry, aspect angle, and varying lines-of-sight towards the binary components, and improving our understanding of the physical nature of the wind-wind interaction.

In this paper we present results of monitoring of WR 140 in the period 1978 to 1994 with the *International Ultraviolet Explorer (IUE)* Short Wavelength spectrograph. Observations and data reduction are described in Section 3.2. The analysis, in Section 3.3, includes (i) a radial-velocity study based on the O component absorption lines; (ii) a study of the continuum flux variations as a function of orbital phase; (iii) a study of the statistical significance of the observed line profile variability; and (iv) a study of the variability of the observed P-Cygni profiles. In Section 3.4 the results are discussed, and Section 3.5 summarizes the conclusions.

Preliminary studies of these data were published by Setia Gunawan et al. (1995a; 1995b).

### 3.2 Observations and data reduction

WR 140 was observed with *IUE* from 1979 to 1994 in 35 SWP (Short Wavelength Prime camera, \( \lambda \lambda 1165–2126 \text{ Å}, \Delta \lambda \approx 0.1 \text{ Å} \)) images, through the large aperture (10” × 20”), mostly in our own programs, at the ESA-*IUE* Observatory in Villafranca, Spain, many of them as service observations.

Most *IUE*-SWP spectra were taken with an exposure time of 120 minutes; SWP data taken with an exposure time of 195 minutes show saturation and could not be used for the emission-line variability study, but were still useful to study the O-star absorption lines. Some spectra were recorded in shorter exposure times caused by time-loss during hand-over between the NASA and ESA ground-stations. The log of observations is presented in Table 3.1. The orbital phases were calculated from the weighted means of the orbital parameters resulting from this study and those of Paper I.

The spectra were extracted from photometrically corrected PHOT-images, except the first two *IUE*-SWP spectra (SWP6945 and SWP8004) which were extracted from GPHOT-images, using the STARLINK IUEDR software package (Rees et al. 1996a; 1996b). After correction for order-overlap using the algorithm of Bianchi & Bohlin (1984), the wavelength shift was removed by aligning on several narrow interstellar lines. Subsequently, ripple-correction was applied to the *IUE*-SWP images following Barker (1984). The spectra were then mapped onto an equidistant wavelength grid with intervals of 0.1 Å. The flux in the resulting spectra is given in units of *IUE* Flux Number per second (FN/s). Absolute calibrated spectra can be retrieved from the INES system (Cassatella 2000).

Analysis of the data was performed by using the STARLINK DIPSO software package (Howarth et al. 1998). The gaps in the spectra caused by reseau marks were removed by three-point interpolation at either side of the gaps. This caused discontinuities in some spectra where the gaps are too wide. In those cases no interpolation was performed.
3.3 Analysis

3.3.1 Radial velocity study

For the purpose of measuring radial velocities of the absorption lines of the O component of the WR 140 system, we used a Cross-Correlation Function method (CCF, Stickland & Lloyd 1990). The IUE-swp spectra of WR 140, aligned on interstellar lines, were compared with the archive IUE spectrum of the single O4V star HD 96715. The orbital parameters were derived by means of the program RVORBIT by Hill (DAO, private communication). The single-lined radial-velocity curve is shown in Fig. 3.1 and the resulting orbital parameters

<table>
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<tr>
<th>IUE-swp number</th>
<th>JD t_{exp}</th>
<th>φ</th>
<th>RV (km s(^{-1}))</th>
<th>O–C (km s(^{-1}))</th>
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<td>34.3</td>
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<td>50708</td>
<td>2,440,000+</td>
<td>120</td>
<td>0.147</td>
<td>20.4</td>
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</table>
Figure 3.1— The IUE UV single-lined (absorption-line) radial-velocity curve of the O4-5 companion of WR 140, applying as fixed period $P = 2900$ d, following Paper I. The data taken before the 1985.26 periastron passage are marked with $\square$ symbols; those between the 1985.26 and 1993.2 periastron passages are marked with $\bullet$ symbols; and those after the 1993.2 periastron passage are marked with $\blacksquare$ symbols. The ensuing orbital parameters are given in Table 3.2.

are listed in Table 3.2, column (3). We emphasize that this UV radial-velocity solution is independent from measurements and solutions at other wavelengths, apart from the adoption of the IR photometric period of $P = 2900$ d. In particular, the high velocities immediately preceding the 1993 periastron passage, which greatly influence the elements determined, were observed three cycles later than the corresponding (1969) optical data used for the solution in Paper I. Column (2) of Table 3.2 lists the orbital parameters of Paper I; we note the good correspondence. Column (4) lists the combined orbital parameters, weighted by $\sigma^{-0.5}$. The corresponding orbital phases per IUE observation are given in Table 3.1.

The position of the O star with respect to the WC star at the times of the IUE observations, on the basis of the averaged orbital parameters, is shown in Fig. 3.2. The figure demonstrates that owing to the large eccentricity, both conjunctions are very close to periastron passage, occurring at $\phi = 0.957$ (O star in front) and $\phi = 0.010$ (O star behind).

An attempt to measure the radial velocities of emission lines of the WC component of WR 140 in comparison with those of a single WC7 star, to obtain a double-lined radial-velocity solution, did not lead to significant results. This is due to line-width differences between individual WC7 stars and severe blending of WC7 emission lines.

The eccentricity $e = 0.87 \pm 0.05$ derived in this study agrees well with the value $0.84 \pm 0.04$ calculated in Paper I from optical spectra. The UV data suggest that periastron passage occurs $104 \pm 117$ days earlier than derived in Paper I. The large error bar is caused by the limited amount of data obtained during periastron: we do not have sufficient coverage before the 1985 periastron (at phases $0.4 < \phi < 1.0$) and at the time of the 1993 periastron the position of WR 140 was violating the IUE Sun-constraint. Another indication that periastron
3.3 Analysis

Figure 3.2— The WR 140 binary orbit, showing the positions of the O-type component in the rest-frame of the WR component at the epochs of the IUE observations listed in Table 3.1. Orbital parameters $e$ and $\omega$ are weighted means of this study and Paper I. The numbers next to the O star positions give the orbital phases.

Table 3.2— Orbital parameters of WR 140 from this UV RV solution and from the optical RV solution of Paper 1.

<table>
<thead>
<tr>
<th>Orbital Parameters</th>
<th>Paper I (optical)</th>
<th>This Study (UV)</th>
<th>Weighted Mean (optical+UV)</th>
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</thead>
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<td>$P$ (d)</td>
<td>2900±10</td>
<td>9060±29</td>
<td>9054±34</td>
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<td>$T_{\text{periastron}}$ (JD 2,440,000+)</td>
<td>8960±172</td>
<td>8947±117</td>
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<tr>
<td>$e_{\text{max}}$ (JD 2,440,000+)</td>
<td>0.84±0.04</td>
<td>0.87±0.05</td>
<td>0.85±0.04</td>
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<tr>
<td>$\omega$ (°)</td>
<td>32±8</td>
<td>31±9</td>
<td>32±8</td>
</tr>
<tr>
<td>$\gamma$ (km s$^{-1}$)</td>
<td>-0.4</td>
<td>23°±1</td>
<td></td>
</tr>
<tr>
<td>$K$ (km s$^{-1}$)</td>
<td>28±3</td>
<td>25±15</td>
<td>28±3</td>
</tr>
<tr>
<td>$a_{\text{0 X star}}$ sin $i$ (AU)</td>
<td>3.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f(M)$ (M$\odot$)</td>
<td>0.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduced $\chi^2$</td>
<td>2.37</td>
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<tr>
<td>RMS (km s$^{-1}$)</td>
<td>3.47</td>
<td></td>
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</tr>
</tbody>
</table>

Notes:  
- a: IR photometric period.  
- b: 6160±29+2900d.  
- c: relative to HD 96715.
occurs earlier, stems from the ASCA X-ray study of WR 140 by Zhekov & Skinner (2000), who argued that periastron occurs 72 days earlier than derived in Paper I.

Our least-squares fit of the radial-velocity curve has a relatively small rms-error of 3.5 km s\(^{-1}\). From the orbital elements resulting from this UV radial-velocity study, we derive for the O-star orbit a semi-major axis \(a_0 \sin i = 3.29\) AU and a mass function \(f(M) = M_\text{WR}^2 \sin^2 i / (M_\text{WR} + M_0)^2 = 0.56\) \(M_\odot\). Assuming for the mass of the O4-5 component \(M_0 = 38\) \(M_\odot\) (Paper I) and \(i = 60^\circ\) would imply that \(M_\text{WR} = 13\) \(M_\odot\).

As to other UV spectroscopic binary orbits for WR stars, a double-lined orbital solution from IUE UV radial-velocity measurements has been derived for WR 11 (\(\gamma^2\) Vel, WC8+O7.5III-V, Stickland & Lloyd 1990; Lloyd & Stickland 1999b). Efforts to find an IUE UV radial-velocity solution for WR 79 (HD 152270, WC7+O5-8) have not succeeded yet (Stickland 1998).

### 3.3.2 The ultraviolet continuum flux

As discussed earlier in Paper I (its section 3.4), there is scant evidence for significant variation in the overall luminosity of WR 140. Recently, Panov et al. (2000) monitored WR 140 from 1991 to 1998 in \(UBV\) photometry. They observed in 1993 a dip in the light curve in all passbands around periastron passage, with a \(V\)-amplitude of 0.03 mag.

In the ultraviolet, Paper I sampled the flux level of the line-free UV continuum around 1800 Å from low resolution \(IUE\) spectra available at that time. Here we use the 35 absolute flux calibrated \(IUE\) spectra of WR 140 retrieved from the INES system (Cassatella 2000). From 34 spectra (excluding the overexposed SWP-9492), we measure a mean flux level of \(7.8 \pm 0.2 \times 10^{-12}\) erg s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\). The flux levels are plotted against orbital phase in Fig. 3.3. The amplitude of the scatter is \(\sim 8\%\), and, as in Paper I, we have to regard vari-

![Figure 3.3](image_url)

**Figure 3.3**— Ultraviolet continuum fluxes from the absolute calibrated \(IUE\)-SWS high-resolution spectra of WR 140 in the wavelength region 1790–1800 Å. The excess point at \(\phi = 0.406\) is due to overexposure. Symbols as in Fig. 3.1
### Table 3.3— Equivalent widths $W_{\lambda}$ of the $\lambda 1400$ Å and $\lambda 1720$ Å P-Cygni emission and absorption features in WR 140, at $\phi = 0.5$ when wind-wind interaction is expected to be at a minimum, and in single WC7 and O3-5 stars.

<table>
<thead>
<tr>
<th>Star</th>
<th>Spectral Type</th>
<th>SWP No.</th>
<th>1400 Å Abs. $W_{\lambda}$ (Å)</th>
<th>1400 Å Em. $W_{\lambda}$ (Å)</th>
<th>1720 Å Abs. $W_{\lambda}$ (Å)</th>
<th>1720 Å Em. $W_{\lambda}$ (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WR 140</td>
<td>WC7pd+O4-5</td>
<td>35886</td>
<td>9.6±0.3</td>
<td>-12.5±0.32</td>
<td>0.3±0.1</td>
<td>-5.9±0.3</td>
</tr>
<tr>
<td>WR 90</td>
<td>WC7</td>
<td>15130</td>
<td>11.0±0.4</td>
<td>-14.5±0.48</td>
<td>1.0±0.2</td>
<td>-12.2±0.7</td>
</tr>
<tr>
<td>$\zeta$ Pup</td>
<td>O4I(n)f</td>
<td>36143</td>
<td>6.0±0.2</td>
<td>-2.0±0.23</td>
<td>4.4±0.2</td>
<td>-2.9±0.2</td>
</tr>
<tr>
<td>HD 190429A</td>
<td>O4If+</td>
<td>38994</td>
<td>6.5±0.4</td>
<td>-2.0±0.48</td>
<td>4.2±0.5</td>
<td>-1.8±0.3</td>
</tr>
<tr>
<td>HDE 269698</td>
<td>O4If+</td>
<td>06967</td>
<td>6.8±0.5</td>
<td>-2.1±0.49</td>
<td>4.2±0.5</td>
<td>-1.7±0.3</td>
</tr>
<tr>
<td>HDE 269810</td>
<td>O3III(f*)</td>
<td>10755</td>
<td>5.1±0.5</td>
<td>-1.3±0.39</td>
<td>3.3±0.4</td>
<td>-2.0±0.4</td>
</tr>
<tr>
<td>HD 15558</td>
<td>O5III(f)</td>
<td>08322</td>
<td>4.8±0.5</td>
<td>-1.1±0.56</td>
<td>4.8±0.5</td>
<td>-1.9±0.3</td>
</tr>
<tr>
<td>9 Sgr</td>
<td>O4V((f))</td>
<td>15307</td>
<td>0.8±0.3</td>
<td>—</td>
<td>0.4±0.2</td>
<td>-0.8±0.3</td>
</tr>
<tr>
<td>HD 46223</td>
<td>O4V((f))</td>
<td>38730</td>
<td>3.7±0.4</td>
<td>-1.0±0.34</td>
<td>2.9±0.4</td>
<td>-1.2±0.3</td>
</tr>
<tr>
<td>HD 96715</td>
<td>O4V((f))</td>
<td>10757</td>
<td>1.2±0.2</td>
<td>-0.7±0.23</td>
<td>2.3±0.2</td>
<td>-0.5±0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>22000</td>
<td>1.2±0.2</td>
<td>-0.0±0.27</td>
<td>2.0±0.2</td>
<td>-0.5±0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.1±0.6</td>
<td>-0.3±0.74</td>
<td>2.4±0.3</td>
<td>-0.7±0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.7±0.3</td>
<td>-0.4±0.30</td>
<td>2.9±0.4</td>
<td>-0.5±0.4</td>
</tr>
</tbody>
</table>

3.3.3 The luminosity of the O component

We compare the WR 140 WC7pd+O4-5 $IUE$ spectrum with that of the single WC star WR 90 in Willis et al. (1986), and with those of single O4-5 stars presented in Walborn et al. (1985). We measured the equivalent widths of absorption and emission parts of the P-Cygni profiles at around 1400 Å ($\text{Si}IV$) and 1720 Å ($\text{N}IV$), and list them in Table 3.3. WR 140 shows a strong $\text{Si}IV\lambda 1394,1403$ Å P-Cygni resonance doublet and a weak $\text{N}IV\lambda 1719$ Å P-Cygni profile (see Fig. 3.5).

O-type stars show a P-Cygni feature at around 1720 Å due to $\text{N}IV\lambda 1719$ Å. This feature is strongest in O-type supergiants, moderate in O-type giants, and weakest in O-type main-sequence stars. The single O-type supergiants $\zeta$ Pup (O4I(n)f), HD 190429A (O4If+) and HDE 269698 (O4If+) show indeed strong $\text{N}IV\lambda 1719$ Å P-Cygni and strong $\text{Si}IV$ P-Cygni resonance doublet components. The single O-type giants HD 15558 (O5III(f)) and HDE 269810 (O3III(f*)) have weak $\text{N}IV$ and very weak $\text{Si}IV$ P-Cygni resonance lines. The single O-type main-sequence stars 9 Sgr (O4V((f))), HD 46223 (O4V((f))) and HD 96715 (O4V((f))) show weak $\text{N}IV$ absorption and no $\text{Si}IV$ P-Cygni resonance lines.

We observe that the $\lambda 1719$ Å P-Cygni profile in the $IUE$ spectra of WR 140 has an emission/absorption ratio of 20 and that of WR 90 has a ratio of 12. The O-type stars in Table 3.3 have ratios in the range $\sim 0.2$–0.5. Therefore, we suggest that in the case of WR 140 the contribution of the O-companion to that line is only minor and thus more likely from an O-
type main sequence star than a supergiant, where the latter have stronger 1719 Å lines than the former.

The Si IV P-Cygni profile of WR 140 almost exactly matches that of the single WC7 star WR 90 (see Willis et al. 1986) in its strong emission/absorption ratio of $\sim 1.3$, while the O-type stars in Table 3.3 have ratios in the range $\sim 0.3–0.4$. This indicates that in WR 140 the Si IV P-Cygni resonance-line originates mainly in the WC7 component.

From the comparisons made above, we conclude that the O-type component of WR 140 is more likely a main-sequence star.

An alternative way to determine the luminosity of the O component is provided by van der Hucht (2001). By comparing the equivalent widths of the C IV $\lambda$5808 Å, C III $\lambda$4650 Å, C III $\lambda$5696 Å and O III/IV $\lambda$5592 Å emission lines of WR 140 with those of the five apparently single WC7 stars WR 14, WR 50, WR 56, WR 68, and WR 90 (Conti & Massey 1989; Smith et al. 1990), he found for WR 140 that $\Delta M_v = M_v^{\text{omp}} - M_v^{\text{WC7}} = -0.6 \pm 0.3$. From a study of galactic WR stars in open clusters and associations, he derived that $M_v^{\text{WC7}} = -4.5 \pm 0.7$ for single WC7 stars. Thus $M_v^{\text{omp}} = -5.2 \pm 0.5$. This corresponds to the luminosity of a O3-8 V star or a O6.5–7 III star (Vacca et al. 1996), consistent with the result derived above.

From an evolutionary point of view, it would be very unlikely to have two evolved components (i.e., WR+ OI) in one system.

### 3.3.4 Statistical significance of the observed variability

The UV spectra of WR 140 show variations with orbital phase, because the lines-of-sight towards the two binary components probe at different times different regions of the O-star wind, the WR wind and the shock cone of the wind-wind collision region between the two stars.

The significance level of variability in our spectra is expressed in a Temporal Variance Spectrum (TVS), following Fullerton et al. (1996). In this method the observed variance in flux in each wavelength bin (0.1 Å) is compared to the variance due to instrumental and photon noise (at a corresponding flux level). The TVS can be approximated by:

![Figure 3.4](dots: S/N ratio as a function of $F_\lambda$ determined from 35 IUE-SWP spectra of WR 140 at 4134 different wavelengths. Curve: best fit of a two-parameter function, see Eq. 3.2.)
FIGURE 3.5 — **Black line**: average of 35 WR 140 IUE-sw spectra sampled at 0.1 Å resolution in the 1150–1960 Å range. Relevant variable features are visible at \( \lambda \lambda 1330 \text{ Å}, 1400 \text{ Å} \) and 1550 Å, corresponding to the resonance lines of C II, Si IV and C IV, respectively. Sharp absorption features are of interstellar origin. **Light line**: The Temporal Sigma Spectrum (TSS), i.e., the corresponding \( \sigma \)-ratio, with amplitude characterizing the variability (Section 3.3.4). Slight mismatches in wavelength calibration introduce peaks in the TSS, especially at the position of sharp lines.
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Figure 3.6— Configurations of the WR 140 system as a function of phase shown in the plane of the orbit and reference frame of the WC component (marked). The O4-5 star orbits clockwise in this illustration, as does the wind-interaction region, marked by the contact discontinuity between the WC and O stellar winds. The form of the contact discontinuity is determined from the momenta of the two winds (Eichler & Usov 1993) and the relative velocities of the stellar winds and orbital motion. The changing sightlines to the two stars are shown.
3.3 Analysis

\[ (TVS)_\lambda \simeq \frac{1}{(N - 1)} \sum_{i=1}^{N} \left[ \frac{F_i(\lambda) - F_{av}(\lambda)}{\sigma_i(\lambda)} \right]^2, \]  

(3.1)

where \( N \) is the number of spectra, \( \sigma_i(\lambda) \) is the standard deviation due to instrumental and photon noise, \( F_i(\lambda) \) is the flux of the \( i \)-th spectrum and \( F_{av}(\lambda) \) is the average spectrum.

The problem is to determine \( \sigma_i \). Henrichs et al. (1994) found that for IUE spectra \( \sigma_i \) can be expressed as a function of flux only, by measuring the standard deviation of a set of spectra in each wavelength bin, excluding regions containing the variable spectral lines or where the echelle orders do not properly overlap. The ratio of \( F_{av}(\lambda) \) over \( \sigma(\lambda) \), representing the S/N ratio, is fit with the function (see Fig. 3.4):

\[ \frac{F}{1.8 \pm 0.05} \cdot \tanh \left( \frac{F}{1.8 \pm 0.05} \right). \]  

(3.2)

This function is used to specify \( \sigma_i \) for a given \( F_i \) in Eq. 3.1. To calculate the error in the S/N, we assumed a Poisson-distribution giving a reduced \( \chi^2 = 1.0 \). The asymptotic value of S/N = 13.6 fits our spectra best. We used the fit-function above to represent the S/N of all available WR 140 IUE spectra, and to calculate the \( \sigma(\lambda) \). Next, we calculated the TVS value. Subsequently, we derived the TemporalSigma Spectrum (TSS), which can be approximated by \( \sqrt{TVS} \). This TSS can be considered as the ratio of the observed (\( \sigma_{obs} \)) to the expected (\( \sigma_{exp} \)) standard deviation and is a direct measure of the amplitude (and significance) of the variability.

The average spectrum and the corresponding \( \sigma \)-ratio of the IUE-SWP spectra of WR 140 are shown in Fig. 3.5. Only the strongest features are identified. More complete spectral line identifications of WC7 emission features are listed by Willis et al. (1986) for the single WC7 star WR 90 (HD 156385). In the available spectral regions, \( \sigma_{obs}/\sigma_{exp} > 1 \) indicates variability. The larger the ratio, the stronger the degree of variability. We observe strong, broad variability around \( \lambda \lambda 1330 \AA, 1400 \AA \) and \( 1550 \AA \). Those wavelength regions correspond to the resonance lines of C II, Si IV and C IV, respectively, and are discussed below.

### 3.3.5 Variable P-Cygni resonance line profiles

#### 3.3.5.1 Lines present

All available spectra were scaled to the same flux level by conserving the total flux in the wavelength regions \( \lambda \lambda 1435–1500 \AA, 1565–1605 \AA \) and \( 1740–1840 \AA \), where the spectra have relatively few features. In Fig. 3.8 we show a dynamic spectrum of the UV resonance doublet of C II \( \lambda \lambda 1335,1336 \AA \), in Fig. 3.9 that of Si IV \( \lambda \lambda 1394,1403 \AA \), and in Fig. 3.10 that of C IV \( \lambda \lambda 1548,1551 \AA \), all in grey-scale representation. Orbital phase at the time of each observation is indicated by an arrow along the vertical scale. The horizontal scale represents the velocity with respect to the rest wavelength of the principal doublet line. Strong variations occur in the absorption part of the P-Cygni profiles around periastron passage (\( \phi = 0 \), see Fig. 3.2 for the geometry of the system).

#### 3.3.5.2 Lines varying

In order to visualize the changing sightlines to the two binary components as a function of orbital phase, we plot in Fig. 3.6 eight different configurations, with increasing phase running clockwise. For most of the orbit, the WC star is observed through its own wind. Only
around conjunction ($\phi = 0.957$), the phase interval depending on the orbital inclination and the opening angle of the wind-collision cone, can the sightline pass through the O star wind instead of the outer reaches of the WC wind. The O-type star, on the other hand, is observed through both part of the O stellar wind and, apart from a phase interval around conjunction, a varying sightline through the WC stellar wind whose optical depth and velocity range depend on phase. Because the O-type star is the brighter component and the WC wind has the greater optical depth, these variations have a significant influence on the observed spectrum. We note the following situations:

1. Quadratures occur at $\phi = 0.996$ and 0.114. Between these phases, the O star is more distant than the WC star and is observed through both red-shifted and blue-shifted WC wind material. Both the velocity and the optical depth are at maximum at $\phi = 0.008$ and the effects of this are clearly seen in the Si IV and C IV observations (Figs. 3.7, 3.9, 3.10)

2. From $\phi = 0.114$ to about $\phi = 0.5$, and depending on the inclination of the orbit, the sightline to the O-star passes through less of the WC stellar wind. At the same time, as the angle between the sightline and the wind falls, the velocity range covered by the P-Cygni absorption falls and approaches the terminal wind velocity. This is also seen in the evolution of the absorption features, particularly Si IV. This is also consistent with the view (Section 3.3.3 and Table 3.3) that the Si IV is formed mainly in the WC7 star.

3. As the orbit progresses, this evolution continues until $\phi \geq 0.85$ (depending on orbital inclination), our sightline to the WC7 star also passes through the O star wind until conjunction at $\phi = 0.957$. Our spectrum at this phase (SWP 46119) is not of the highest quality but the Si IV absorption does appear to be weakest at this phase.

### 3.3.5.2.1 Line-eclipse spectra

In order to visualize what happens around periastron, we took the ratio of the C II, Si IV and C IV profiles observed at $\phi = 0.010$ (O star behind the WR star in the line-of-sight, see Fig. 3.6) over the average of the 19 spectra observed at $0.5 < \phi < 1.0$ (O star in front of the WR star wind in the line-of-sight). We verified that all spectra between $\phi \sim 0.5$ and $\phi = 0.957$ are almost similar. The result, displayed in Fig. 3.7, shows ‘eclipse’ spectra in those lines at phase $\phi = 0.010$, i.e., very close to periastron. We observe again that the C IV and Si IV resonance lines show at periastron excess absorption with $v_{\text{black}} \simeq -3200 \text{ km s}^{-1}$, i.e., $\sim 400 \text{ km s}^{-1}$ faster than at quiescence.

The excess UV absorption occurs at the same phases as the excess X-ray absorption (Paper I).

The broad, shallow absorption features in the Si IV and C IV ratios are formed in the red-shifted WC wind material as noted above. The Si IV profile extends to about +3400 km s$^{-1}$, interpreted as a red shift of the $\lambda 1403$ component by +1250 km s$^{-1}$. The profile shows a discontinuity near this velocity which we attribute to the redshift of the stronger $\lambda 1394$ component. Similarly, we interpret the +2000 km s$^{-1}$ redward extension of the C IV profile as a red shift of the $\lambda 1551$ component by +1500 km s$^{-1}$. These redshifts are interpreted as the maximum component of the WC stellar wind in our sightline to the O star and can be used to estimate the inclination of the orbit. Assuming no radiative braking, the maximum velocity is $v_{\text{black}} \sin(i - \theta')$, where $i$ is the orbital inclination and $\theta'$ the angle above the orbital plane subtended at the WC star by the intersection of the sightline and the wind contact discontinuity. The value of $\theta'$ is found from $i$ and the wind parameters using Eqn. 24 of Cantó et al. (1996) to be $\theta' \simeq 10^\circ$. A +1350 km s$^{-1}$ maximum redshift then implies an orbital inclination
Fig. 3.7— Ratio of the IUE spectra of WR 140 at $\phi = 0.010$ (O star behind the WR star in line-of-sight) and the average of 19 IUE spectra with $0.5 < \phi < 1$ (O star in front of the WR star wind in line-of-sight, see Fig. 3.2) for the C II, Si IV, and C IV resonance lines, giving ‘eclipse’ spectra.

$i = 38^\circ$. Owing to the difficulty of fitting the absorption profiles and the possibility of radiative braking, this may be a lower limit, but does suggest that the orbit of WR 140 is not greatly inclined.

3.3.5.2.2 The C II $\lambda\lambda 1335, 1336$ Å resonance lines
The time-variable C II resonance P-Cygni line profiles (Fig. 3.8) show a significant non-variable narrow absorption dip in both doublet components at a constant velocity of about $-3100 \text{ km s}^{-1}$, reminiscent of the narrow absorption components seen in O-type stars (Kaper et al. 1996). These represent very likely the signature of the terminal wind velocity of the O component.

Although the absorption part of the red doublet component is contaminated by the emission part of the blue doublet component, we observe for both doublet components a similar tendency of variability: the absorption features are broader and deeper right after periastron passage ($\phi = 0$).

At the blue end of these absorption features we measure $v_{\text{black}} \approx -2800 \text{ km s}^{-1}$ at all phases. At periastron passage no change in $v_{\text{black}}$ is observed, contrary to what happens in the C IV and Si IV resonance line profiles (see below). However, at periastron the red black-edge of the C II P-Cygni absorption trough abruptly expands from about $-2800 \text{ km s}^{-1}$ to $-1800 \text{ km s}^{-1}$. The red black-edge of the C II absorption trough is back to quiescence at $\phi \approx 0.6$, when the the line-of-sight passes through rather more of the O star wind and less of the WC stellar wind (see Fig. 3.6).
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FIGURE 3.8 — The C II resonance doublet of WR 140 in grey-scale representation. Epochs of observation are indicated by arrows. The horizontal scale represents velocity with respect to the rest-wavelength of the principal doublet component. The interstellar doublet components of the C II resonance line mark the rest-wavelengths. At periastron ($\phi = 0$), the absorption troughs of the P-Cygni profiles become deeper and broader. The spectrum at $\phi = 0.406$ (SWS9492) is overexposed.

3.3.5.2.3 The Si IV $\lambda\lambda1394,1403$ Å resonance lines
Although the absorption part of the red doublet component is contaminated by the emission part of the blue doublet component, we observe for both Si IV doublet components a similar tendency of variability: the absorption features are broader and deeper right after periastron
passage ($\phi = 0$), and even become saturated.

At the blue end of these absorption features we measure $v_{\text{black}} \simeq -2800 \text{ km s}^{-1}$ for $0.3 < \phi < 0.96$, i.e., during quiescence. Just after periastron passage ($\phi = 0$), $v_{\text{black}}$ increases abruptly to about $-3200 \text{ km s}^{-1}$. At phase $\phi \simeq 0.3$, $v_{\text{black}}$ has gradually returned back to about $-2800 \text{ km s}^{-1}$.

Also just after periastron passage, the red black-edge of the Si IV P-Cygni absorption trough abruptly expands from about $-2600 \text{ km s}^{-1}$ to about $-2000 \text{ km s}^{-1}$. Thus, at $\phi \simeq 0$ the
Si IV black absorption trough has a total extent from about −3200 to −2000 km s\(^{-1}\). In addition, as can be seen clearly in Fig. 3.9, overall excess red absorption extends to +3400 km s\(^{-1}\).

The blue black-edge of the Si IV absorption trough is back to quiescence at \(\phi \approx 0.2\); the red black-edge of the Si IV absorption trough is back to quiescence at \(\phi \approx 0.4\).

The time-variable Si IV resonance P-Cygni line profiles (Fig. 3.9) show a significant non-variable narrow absorption feature with approximately the same wavelength separation as the Si IV doublet components at a constant wavelength, corresponding to a Si IV velocity of...
about −3700 km s$^{-1}$. However, since at that velocity no absorption features are seen in other P-Cygni profiles of WR 140, these absorption features must be of O star photospheric origin.

3.3.5.2.4 The C$\text{IV}$ λλ 1548,1551 Å resonance lines

Although the absorption troughs of both C$\text{IV}$ doublet components largely overlap, we observe for both a similar tendency of variability: the saturated absorption features are broader right after periastron passage ($\phi = 0$).

At the blue end of these absorption features we measure $v_{\text{black}} \simeq -2800$ km s$^{-1}$ for $0.6 < \phi < 0.96$, i.e., during quiescence. Just after periastron passage, $v_{\text{black}}$ increases abruptly to about $-3200$ km s$^{-1}$. At phase $\phi \simeq 0.6$, $v_{\text{black}}$ has gradually returned back to about $-2800$ km s$^{-1}$.

Also at periastron the red black-edge of the C$\text{IV}$ P-Cygni absorption trough abruptly expands from about $-2600$ km s$^{-1}$ to about $-1700$ km s$^{-1}$. Thus, at $\phi \simeq 0$ the C$\text{IV}$ black absorption width has a total extent from about $-3200$ to $-1700$ km s$^{-1}$. In addition, as can be seen clearly in Fig. 3.10, overall excess red absorption extends to $+2000$ km s$^{-1}$.

The blue and red black-edges of the C$\text{IV}$ absorption trough are back to quiescence at $\phi \simeq 0.6$ when the line-of-sight passes through rather more of the O star wind and less of the WC stellar wind (see Fig. 3.6).

The time-variable C$\text{IV}$ resonance P-Cygni line profiles (Fig. 3.10) show a faint non-variable narrow absorption feature in both doublet components with approximately the same wavelength separation as the C$\text{IV}$ doublet components at a constant wavelength difference, corresponding to a C$\text{IV}$ velocity of about $-3400$ km s$^{-1}$. However, since at that velocity no absorption features are seen in other P-Cygni profiles of WR 140, these absorption features must be of O star photospheric origin. IUE spectra of single OV-type stars show absorption features at the same wavelengths (Walborn 1985).

It appears that the C$\text{II}$, C$\text{IV}$ and Si$\text{IV}$ resonance lines behave identically, the difference being the optical depth.

3.3.5.2.5 Other spectral lines

At 1640 Å, the wavelength of the strongest He$\text{II}$ emission line, we find no significant variability. In contrast, IUE spectra of the WN binaries HD 90657 (WR 21, WN5+O4-6), V444 Cyg (WR 139, WN5+O6III-V), and GP Cep (WR 153, WN6/WCE+O6I) show variable He$\text{II}$ λ1640 Å emission-line strength when the O star is in front of the WR star in the line-of-sight (Koenigsberger & Auer 1985).

We also looked for variability in the N$\text{V}$ λλ 1239,1243 Å resonance doublet, which we expect to be observable from the O-star wind only. Unfortunately, this line is blended by the absorption part of the WC C$\text{III}$ λ 1247 Å P-Cygni profile (not a resonance line, not variable) and the S/N ratio is rather low in this part of our IUE spectra.

3.4 Discussion

In general, when the inclination of a WR+O colliding wind binary causes wind occultation effects, we can expect the observed wind velocities reflected in the blue black-edges of the P-Cygni absorption troughs to vary between the wind terminal velocities of the individual WR star and O star.

In the absorption part of the Si$\text{IV}$ P-Cygni profile (Fig. 3.9), the blue black-edge of the absorption trough, i.e., the apparent terminal wind velocity, increases with $\Delta v_\infty \simeq 400$ km s$^{-1}$
to $v_\infty \approx 3200 \text{ km s}^{-1}$, when the O star in its orbit passes the WC star at periastron ($\phi \approx 0$) and moves behind it in the line-of-sight (see Fig. 3.6). In Section 3.3.3 we concluded that the Si IV $\lambda \lambda 1394,1403$ Å resonance-line doublet originates only in the WC7 star. Even if the O component contributed to that line, the increase to maximum blue-shifted velocity of $-3200 \text{ km s}^{-1}$ at $\phi = 0$ cannot have been caused in the O star wind alone, because the O star wind provides minor absorption compared to the much denser WC star wind. The O star light in the line-of-sight at $\phi = 0$ is being absorbed by both the O-star wind and the WC-star wind matter. Thus the apparent $\Delta v_\infty$ occurs when the line-of-sight to the O star passes very close to the WC star (due to a high inclination of the binary orbit) through the WC wind.

Contrary to this, the C II $\lambda \lambda 1335,1336$ Å and C IV $\lambda \lambda 1548,1551$ Å resonance lines originate in both binary components. This can be seen clearly in the C II profile (Fig. 3.8), where two sets of shifted doublet components are present. One set is blue-shifted by about $-2800 \text{ km s}^{-1}$, and the other set, slightly fainter, is blue-shifted by about $-3100 \text{ km s}^{-1}$. The set with higher velocity shows a consistent brightness throughout the orbit while the set with lower velocity shows variability. The absorption profile is very broad just after periastron and gradually becomes narrower until around phase $\phi \approx 0.4–0.6$, whereafter the absorption trough becomes relatively weak. The larger velocity is reminiscent of the terminal wind velocities $v_\infty \approx 3200 \text{ km s}^{-1}$ for O4-5 stars (Conti 1988). The smaller velocity is reminiscent of the observations of WR 140 by Eenens & Williams (1994), who measured $v_\infty(\text{He I} 1.083 \mu) = 2900 \text{ km s}^{-1}$ and $v_\infty(\text{He I} 2.058 \mu) = 2845 \text{ km s}^{-1}$, respectively.

Again, we emphasize that the variability is observed as excess absorption, i.e., in the absorption troughs of the P-Cygni line profiles of C II, Si IV and C IV during and just after $\phi \approx 0$, and almost precisely at $\phi \approx 0$ over the whole P-Cygni profiles of Si IV and C IV. Thus the variations are related to changes in the lines-of-sight towards both stars. When the O star is in front of the WC wind ($0.6 \leq \phi \leq 0.957$, see Fig. 3.6), we observe in the line-of-sight towards the O star through material of the O-star wind and, superimposed, in the line-of-sight towards the WC star through much denser WC wind material (recall that the O-star wind is confined to a cone in the WC-star wind, see Fig. 3.6). For about half of the orbit after periastron ($0 < \phi \leq 0.6$), the dense WC wind is in front of the O star, dominating the absorption in the line-of-sight towards the O star. Thus, only when the O star is in front of the WC star in the line-of-sight ($\phi \approx 0.8–0.9$), does one observe uncontaminated O-star material in the line-of-sight towards that component. Right after periastron passage ($0 < \phi \leq 0.1$), the bulk of the dense WC wind is in front of the O star in the line-of-sight, dominating the circumstellar absorption.

The observed asymmetric velocity increase/decrease is clearly caused by the large eccentricity of the orbit (as concluded in Section 3.3.1), both conjunctions are very close to periastron passage, occurring at $\phi = 0.957$ (O star in front) and $\phi = 0.010$ (O star behind), and the aspect angle, affecting the sightlines towards both binary components as a function of orbital phase.

The increase at periastron in maximum blue velocity (to about $-3100 \text{ km s}^{-1}$) cannot be solely due to absorption in the O star wind (which has the larger wind velocity), because most of the absorption at these orbital phases occurs through the much denser (but slower) WC wind.

We offer the following explanations:

(i) At the stronger-absorption/larger velocity phases ($0 < \phi \leq 0.3$), the sightline to the (brighter) O star passes close to the WC star and through the densest part of its wind, where
3.4 Discussion

<table>
<thead>
<tr>
<th>star</th>
<th>WR 11</th>
<th>WR 137</th>
<th>WR 139</th>
<th>WR 140</th>
</tr>
</thead>
<tbody>
<tr>
<td>type</td>
<td>WC8+O7.5III-V</td>
<td>WC7pd+O9</td>
<td>WN5+O6III-V</td>
<td>WC7pd+O4-5</td>
</tr>
<tr>
<td>e</td>
<td>0.33 ± 0.01</td>
<td>&gt; 0.12</td>
<td>0.04 ± 0.01</td>
<td>0.87 ± 0.05</td>
</tr>
<tr>
<td>i (°)</td>
<td>63 ± 8</td>
<td>78.7±0.5</td>
<td>38</td>
<td>31±9</td>
</tr>
<tr>
<td>ω (°)</td>
<td>68</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>resonance lines</td>
<td>1450 700</td>
<td>1900 300</td>
<td>1700 1200</td>
<td>2800 400</td>
</tr>
</tbody>
</table>

Note: Stellar parameters are from the compilation of van der Hucht (2001), except for WR 140 and WR 137, which are from this study.

Anomalously broad emission lines are formed (corresponding to \( \sim 4200 \text{ km s}^{-1} \), Torres et al. 1986). The manifestations of broadening may be caused by turbulence in the wind, probably arising from the wind-wind collision region.

\( (ii)\) If the WR wind is not spherically symmetric but faster at latitudes around the WR star’s equator (likely to be aligned with the orbital plane), then faster sightline absorption due to wind occultation, as observed at \( \phi = 0 \), would be a logical consequence.

\( (iii)\) As a hypothesis, because the luminosity of the O star is about twice that of the WC star, the majority of the UV photons are emitted by the O star. Both stellar winds are driven by radiation pressure; when the separation between the two stars is smallest (the minimum separation is \( \sim 2.35 \text{ AU} \simeq 500 \text{ R}_\odot \), see Paper I) one could expect that common-envelope acceleration by the combined WC and O stellar radiation fields, which is always dominated by that of the O star, is most effective, since this effect scales with the squared separation of the binary components in their eccentric orbit. This, however, would have to be proven through atmospheric modelling, which is beyond the scope of this paper.

\( (iv)\) As a further hypothesis, recent investigations of Gayley (2001) indicate that in massive close binaries enhanced radiatively driven mass loss due to tidal stresses will be focused along the orbiting line of centers. Koenigsberger et al. (2001) explain the variability observed in HD 5980 by this effect.

The long-period WC7pd+O9 binary WR 137, with a period of \( P = 13.1 \text{ yr} \) (Williams et al. 2001), shows in its IUE-sw spectra a behaviour similar to that of WR 140, with an excess \( \Delta v_\infty \simeq 300 \text{ km s}^{-1} \) at periastron.

We find in the literature a couple of other binaries that show excess wind velocities as a function of orbital phase:

\( (a)\) The apparent wind variability phenomena in the IUE spectra of WR 140 (and WR 137) discussed above are reminiscent of those found by St-Louis et al. (1993) in Copernicus and IUE UV spectra of the WC8+O7.5III-V binary \( \gamma^2 \) Velorum (WR 11, \( P = 0.22 \text{ yr}, i \simeq 65^\circ \)).
They argued that the pattern of variability in the UV spectra of $\gamma^2$ Vel can be understood in terms of selected eclipses of the O star light when passing through the WC8 stellar wind, as proposed by Willis & Wilson (1976), combined with an asymmetric wind density due to colliding wind effects. The same IUE data of WR 11 had been interpreted earlier by Brandi et al. (1989), who suggested that the variable $v_\infty$ components observed in the Si IV, C IV and N V resonance line profiles of WR 11 are caused by a jet-stream of gas moving away from the system with a velocity of $\sim -700$ km s$^{-1}$. Applying the correction factor of 0.76 of Prinja et al. (1990), this scales down to a jet outstream velocity of about $-500$ km s$^{-1}$. A similar apparent outstream velocity variability in WR 11 has been observed in monitoring observations of the optical C III $\lambda$ 4650 (non-resonance) emission line by Schweickhardt et al. (1999), who found that the variable component shows a maximum outstream velocity of about $-700$ km s$^{-1}$.

(b) Variable excess emission components have also been observed in the C III $\lambda$ 5696 emission lines of the short-period WC7+O binaries WR 42 ($P = 7.9$ d) and WR 79 ($P = 8.9$ d) by Hill et al. (2000), as a function of orbital phase. They assume, following Lührs’ (1997) earlier study of that emission line in WR 79, that the excess emission arises in the colliding wind regions of the respective WC7+O binaries. In the analytical Lührs model it is assumed that the O star and its wind are embedded in the wind of the WR star, and that the boundary surface is cone-like and rotationally symmetric with respect to the line connecting the two stars. Model fitting of the observed excess emission profiles as a function of phase, allows one to obtain the streaming velocity $v_{\text{str}}$ of material in the cone, among other cone parameters. For WR 42 Hill et al. (2000) find that $v_{\text{str}} \approx 1740$ km s$^{-1}$, while its $v_\infty = 1500$ km s$^{-1}$ (Eenens & Williams 1994); for WR 79 they find that $v_{\text{str}} \approx 2000$ km s$^{-1}$, while its $v_\infty = 2270$ km s$^{-1}$ (Prinja et al. 1990). Apparently their streaming velocities are of the order of magnitude of the terminal wind velocities.

(c) IUE spectra of the short-period ($P = 4.2$ d) WN5+O6III-V close and eclipsing binary V444 Cyg show an excess terminal velocity of $\Delta v_\infty \approx 1200$ km s$^{-1}$ (from about $-1700$ to $-2900$ km s$^{-1}$, but contrary to the three WC cases, only when the O-type star is in front of the WN star (Shore & Brown 1988, their wind velocities scaled down by a factor of 0.76 following Prinja et al. 1990).

(d) The extremely variable medium-period ($P = 19.3$ d, $e = 0.31, i = 88^\circ$) LBV/WR eclipsing binary HD 5980 in the SMC shows only when star B (the WN4 star) is in front of star A (the LBV-type eruptor in the system), i.e., at the time of eclipse of star A, a sudden increase of the C IV P-Cygni absorption edge velocity from $-2500$ km s$^{-1}$ to $-3300$ km s$^{-1}$ (Koenigsberger et al. 2000).

Indications of enhanced, focused winds at periastron have also been found in OB binaries, e.g. in the medium-period ($P = 29.1$ d, $e = 0.764$) O9III+B1III binary $\eta$ Ori (Gies et al. 1996).

The case of WR 140 has also corresponding aspects with the massive binary $\eta$ Car ($P = 5.52$ yr, $e = 0.90$) according to Corcoran et al. (2001), who argue for a phase-dependent mass loss from $\eta$ Car near periastron, on the basis of its X-ray light curve.

In Table 3.4 we summarize the observed velocities from IUE studies of WR 11, WR 137, WR 139 and WR 140. We conclude for all cases, that the observed excess velocities in the spectra of these WR+O binaries are caused by variable absorption in the sightlines to the O stars when passing through their respective turbulent wind-wind collision regions, for the more eccentric orbits enhanced by variable common envelope radiative acceleration.
3.5 Conclusions

From a careful interpretation of a large number of high-resolution IUE spectra of WR 140 (WC7pd+O4-5), we have derived a radial velocity solution and shown the occurrence of substantial resonance line variations in this system. We draw the following conclusions:

1. The large eccentricity of the 7.94 yr orbit is confirmed at $e = 0.87$.
2. The O4-5 component is a main sequence star.
3. Significant changes in the shape of the UV line profiles and strengths are confined to resonance lines of ions expected to be chemically abundant in the WC7 and O4-5 stellar winds.
4. The detailed phase-dependent nature of the line profile changes is found to be consistent with the concept of selective line eclipses of the O4-5 star light by the WC7 stellar wind, affected strongly by the orbital geometry which determines the lines-of-sight to the individual binary components as a function of orbital phase.
5. While it appears clear that line-eclipsing effects are the main cause of the observed UV spectral variability, the detailed line profile changes show that at least some of the eclipsing material is not distributed in a spherically symmetric way around the WC7 star. This is considered to be due to a combination of
   (i) interaction effects involving the collision of the two stellar winds, i.e., turbulence with a large velocity dispersion in the wind-wind collision zone;
   (ii) possible common-envelope acceleration by the combined WC and O stellar radiation fields; and/or
   (iii) the possibility of an orbital-plane enhanced WC7 stellar wind velocity.

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