THE VELOCITY CHARACTERISTICS OF WR STELLAR WINDS

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The stellar winds of hot early-type stars are characterised spectroscopically by the presence of P-Cygni profiles, which are most marked for resonance transitions of common ions and generally occur in the UV, and typical resonance lines of SiIV, CIV, NV and OVI are well known P-Cygni signatures of stellar winds in luminous OB stars. Analyses of these profiles can lead to important information concerning the velocity, density and temperature structure of such winds. The WR stars have more developed stellar winds than OB stars, supporting higher particle densities at larger distances from the stellar "photosphere". Recently Barlow, Smith & Willis, hereinafter BSW, (1980), have derived reliable mass loss rates for 21 WR stars. The mean value is 4×10^{-5} $M_{\odot}/y$ and the rates are considerably larger than can be accomodated by soley radiative models. The, as yet unidentified, mechanism initiating the WR mass loss may also be important for Of stars (Lamers 1980). A determination of the properties of the WR stellar winds will provide diagnostics which might aid in identifying the mass loss mechanism, and P-Cygni profiles form one important data source for this purpose. With the advent of IUE many WR stars have become accessible to high resolution UV spectroscopy for the first time, and this paper briefly reports a first analysis of the UV (and visible) P-Cygni profiles observed in 10 WR stars. A more extensive treatment covering the full results for each star will appear in Monthly Notices. The UV spectroscopy was obtained using the high resolution IUE mode ($\Delta\lambda \simeq 0.1$-0.2Å) in the wavelength range λλ1150-3250. Details of the programme stars are given in Table 1. All the IUE spectra were extracted and reduced using programmes developed at UCL (Giddings 1980) which provide good echelle-interorder background subtraction, accurate tracking of the often distorted individual order spectra, and improved echelle-blaze correction.

1. P-CYGNI PROFILES: VELOCITY MEASUREMENTS

The following transitions, denoted Group I, encompassed in the IUE wavelength range are expected to show well-developed P-Cygni profiles:
NV λ1238.2,λ1242.8 (WN); CIII λ1247.4 (WC); CII λ1334.5,λ1335.7 (WC)
SiIV λ1393.8,λ1402.8 (WN,WC); CIV λ1548.2,λ1550.7 (WN,WC),

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HeII λ1640.4 (WN,WC); NIV λ1718.5 (WN); CIII λ1908.7, λ2296.7 (WC). For each profile the following velocity data have been derived: V_a - corresponding to the violet-shifted edge velocity; V_o - corresponding to the eye-estimated centre of the violet shifted absorption component. In the case of doublets which are unresolved in terms of the breadths of WR spectral features, V_o is measured from the mean doublet wavelength, and V_a from the shorter wavelength component. In addition to Group I lines, the WR stellar winds are sufficiently well developed that higher excitation lines at visible wavelengths often show P-Cygni profiles, denoted Group II lines, and combining these data gives a broad base of E.P. transitions. Velocity data for visible P-Cygni lines have been taken from Bappu (1973) and Seggewiss (1974), and these invariably refer to the central value of the absorption component, corresponding to V_o above. This is often the most accurate, and in many cases the only accurate datum available for features which are often weak and poorly defined. Published values of V_o have been supplemented by data measured from visible spectral tracings of WR stars available at UCL (Smith & Kuhi 1980, Willis & Smith 1980), including stars in common with Bappu and Seggewiss which allows confirmation that their tabulated velocities refer to V_o measurements.

2. CORRELATIONS OF V_o with E.P.

Correlations of the measured values of V_o with E.P. of the transition low level for groups I and II have been inspected for each star and some examples are shown in Fig 1. In each case a well defined correlation of V_o vs. E.P. is found with higher E.P. lines showing the lower velocities reflecting a lowering of excitation conditions in the WR winds with increasing velocity and, assuming an accelerating velocity field with stellar distance. The correlations V_o/E.P. are in some way a measure of the gradient of spectral excitation with velocity (distance) in the winds. A linear least squares fit to these data: $V_o = k + g.(E.P.)$ has been determined for each star and the constants k and g (km/s/eV) in each case are given in Table 1. These fits have then been used to identify further, weaker, features observed in the UV spectra with P-Cygni absorption, producing a further set of V_o data for each star - Group III, which are also marked in Fig 1. Incorporating these new lines in the V_o/E.P. fits did not change the k and g constants significantly. The complete velocity measurements are given by Willis (1981).

In WC spectra Group III lines have been identified in the resonance lines of SiII,III; high excitation lines of CIII,IV and HeII (3-n). Violet-shifted absorption is observed in NV λ1240 in HD 192103 (WC8). In WN spectra Group III features include the resonance lines of SiII,III in WN7,WN8 stars; the HeII (3-n) series and, in WN5,WN6 stars, the NIVλ1486 intercombination line. CIII λ1175 is observed in WN7,WN8 stars and in the WN8 star the resonance lines of AlIII and MgII exhibit P-Cygni profiles. In the case of WN stars (but not in WC) the HeII λ1640 (Bal- α) line shows values of V_o invariably higher than expected. This may be a reflection of the likely dominance of He in WR stars, with this line acting like a pseudo-resonance line. As noted by Seggewiss (1974) the visible

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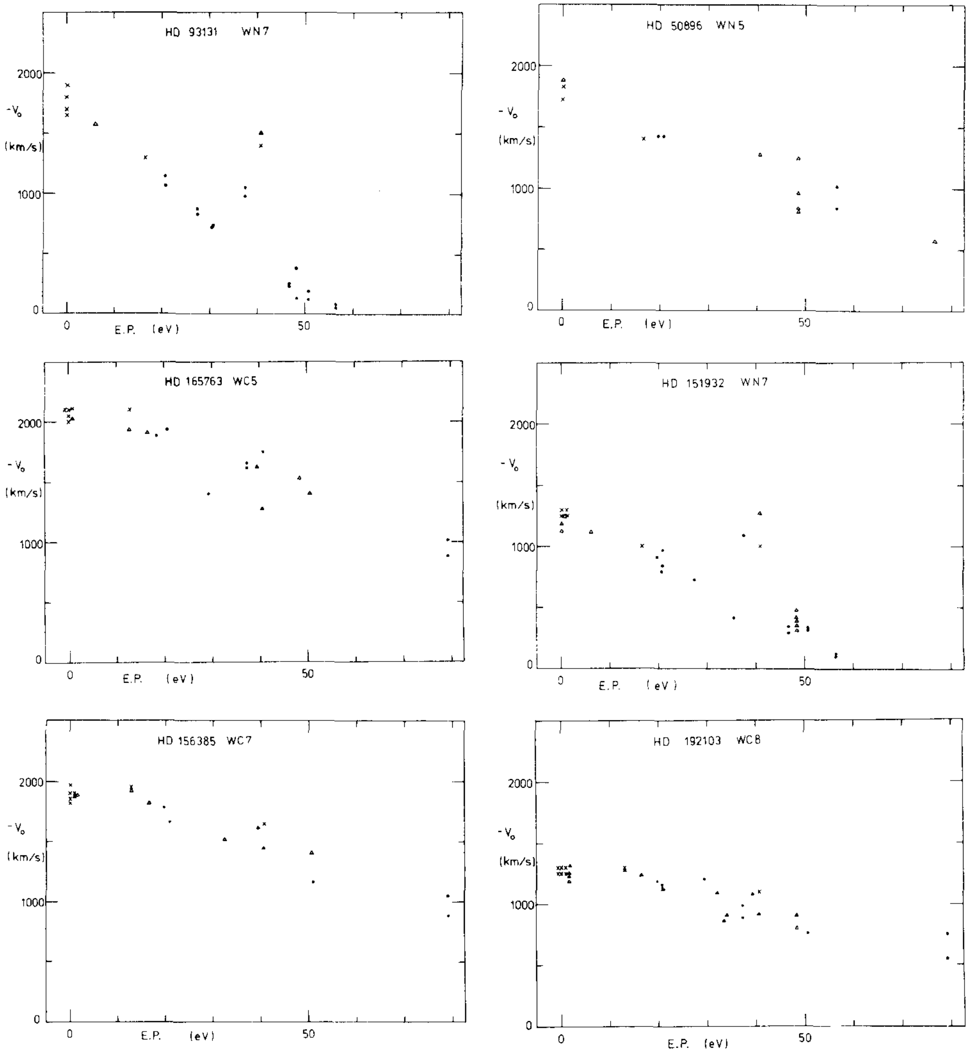

Fig 1: Correlations of V_O with E.P.: key: x are UV Group I lines, Δ are UV group III lines and • are visible Group II lines

Table 1: WR wind V_o/E.P. parameters: k (km/s) and g (km/s/eV)

STAR	SP	k	g	STAR	SP	k	g
HD 50896	WN5	1740	-14.8	HD 151932	WN7	1281	-20.2
HD 191765	WN6	1748	-11.9	HD 96548	WN8	908	-10.8
HD 192163	WN6	1541	-9.5	HD 165763	WC5	2106	-14.0
HD 92740	WN7+O	1434	-24.4	HD 156385	WC7	1911	-12.2
HD 93131	WN7	1747	-31.2	HD 192103	WC8	1302	-8.3

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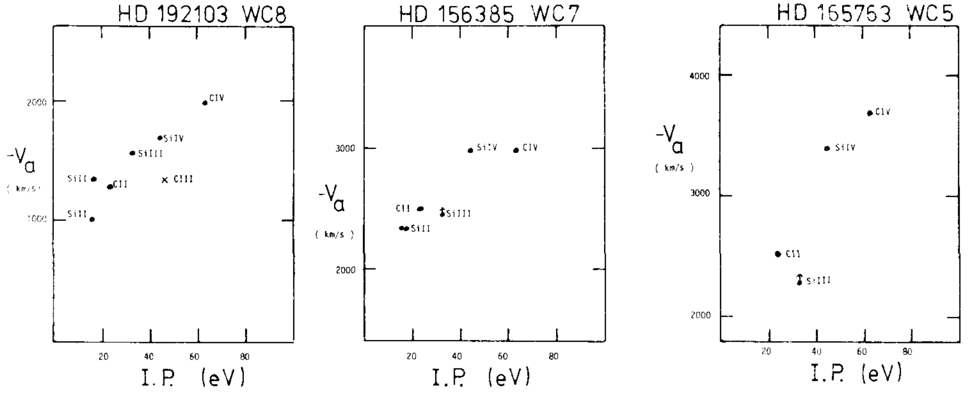
Fig 2: Correlations of UV resonance line edge velocity, V_a, with I.P. in 3 WC stars. Similar trends are seen in WN7, WN8 stars.



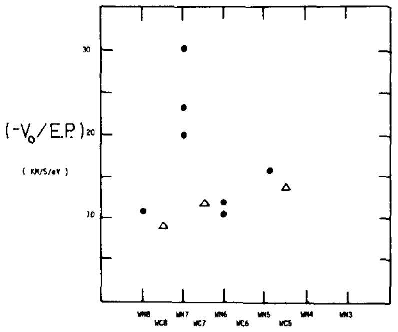
CIV λ5800 lines lie at higher values of V_o than expected, although in our data their behaviour is normal in WN5,WN6 and WC stars.

Only one star in the present sample, HD 92740, is a known binary (Niemela 1980a), and there is no indication in our data that its WR wind has been modified by binary membership: values of k and g for this star are bounded by those for the apparently single WN7 stars HD 93131 and HD 151932. The V_o/E.P. and V_a data for γ-2 Velorum (WC8+O9I) (Willis 1981, Niemela 1980b) show an almost identical behaviour with HD 192103 (WC8) again indicating no binary effects in this case.

3. P-CYGNI ABSORPTION IN HI λ1215 or HeIIλ1215: THE H/He RATIO

All the WR stars in the sample exhibit an absorption feature superimposed on the violet wing of the interstellar Ly-α profile, which can be attributed to wind absorption in either stellar HI (Ly-α) or HeII (Bal-β), either possibility giving essentially the same velocity shift. Since the former line arises from a 0.0 eV level but the latter from a 40.1 eV level, the correlations of V_o/E.P. can be used to distinguish the origin. Detailed discussions for individual stars are given by Willis (1981): here we summarise the conclusions. Stars known to have some H from observations of the visible HeII Pickering decrement (HD 92740, HD 93131 HD 151932 and HD 96548) have clear evidence for HI Ly-α absorption. There is also some evidence for this in the WN6 stars. IN HD 50896 WN5 no HI wind column density is observed, but in this case low ionisation species are generally absent and a atmospheric HI content cannot be ruled out, with a similar situation holding for WC5,WC7 stars. IN HD 192103 WC8 HI absorption is absent but low ionisation SiII wind absorption is clearly seen. Since there is no spread in V_o with I.P. this points to a gross H underabundance in this star, which by implication may also be the case in less unambiguous cases with no apparent HI feature.

Fig 3: (a) Wind gradients, g, in 10 WR stars, (b) mean values of g for WN7, other WR classes and ζPup (O4f). The possible location of intermediate Of-WN7 stars is marked ?



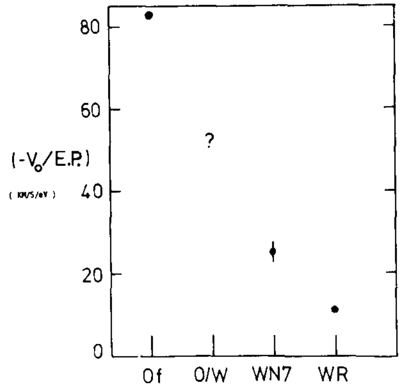


Table 2: WR terminal velocities, V_∞; $\overline{V}_o$ and deduced masses

STAR	V_∞	$\overline{V}_o$	V_{esc}	$R_*(R_\odot)$	$M_*(M_\odot)$
HD 50896	2700	1812±82	900	8.5	18
HD 192163	2400	1510±65	800	10.7	18
HD 191765	2700	1800±75	900	9.5	20
HD 92740	2600	1480±27	866	36.0	71
HD 93131	2900	1760±110	966	36.0	88
HD 151932	2400	1240±61	800	36.0	60
HD 96548	1800	795±124	600	27.0	25
HD 165763	3700	2070±48	1233	8.9	35
HD 156385	3000	1900±43	1000		
HD 192103	2000	1260±41	670	13.2	15

4. STELLAR WIND TERMINAL VELOCITIES

Terminal velocities, V_∞, can be estimated from the edge values, V_a, for the UV resonance lines, taking into account variations of V_a with I.P. For WC stars (Fig 2) (Conti and Van der Hucht 1979) and WN7, WN8 stars there is a marked trend for higher values of V_a with increasing I.P.. Thus edge velocities for CIV and NV have been adopted as V_∞ for WC and WN stars respectively and these data are given in Table 2. A clear correlation of increasing V_∞ with excitation subclass is apparent in WC stars, with a less marked trend in WN stars for which both the stellar sample and variations within a given subclass is greater.

Although we see a strong variation in V_a with I.P. there is not in V_o, implying that the former may not be due to ionisation stratification.

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If it is assumed that the higher I.P. species are dominant throughout the wind then the V_a/I.P. variations might be explained in terms of optical depth effects related to changing particle densities alone. In Table 2 we list the mean and r.m.s. values of V_o for the UV resonance lines. Underhill (1980a,b) has estimated angular diameters and continuum radii for several WR stars in common with our sample. Using the approximate relation: $V_{esc} \simeq 618\ (M_*/R_*)^{\frac{1}{2}}$ and the possibility that WR winds follow the law $V_\infty \simeq 3\ V_{esc}$ (Abbott 1978) one can deduce values of M_* and these data are also given in Table 2. These assumptions can be checked by comparing the deduced masses with those determined independently. Niemela (1980a) finds M(WN7) $\gtrsim 64M_\odot$ and M(WC8) $\gtrsim 17M_\odot$ for HD 92740 and γ-2 Velorum respectively. These values are close to those derived above for HD 92740 and the single WC8 star HD 192103 and suggest that the relation $V_\infty \simeq 3V_{esc}$ holds, implying that the acceleration of WR winds may be governed by the same mechanism (radiation pressure) as in hot luminous OB stars.

5. THE VELOCITY/E.P. GRADIENT IN WR AND O STARS

The correlations of V_o/E.P. shown in Fig 1 indicate a significant gradient in spectral excitation conditions in WR winds; higher values of g implying a more rapid fall with velocity. Values of g for each WR star are plotted vs. subclass in Fig 3a, which shows that for all WR subclasses except WN7, a similar value of g is apparent: the mean being -11.6 ± 2.3 km/s/eV. Values for the WN7 stars are higher and also show a large variation: the mean value being g(WN7) = -25 ± 5 km/s/eV. This result shows a different wind excitation character between WN7 and other WR classes, of probable signifance in view of the proposal that WN7 stars may form an evolutionary link between the Of and WR stars (Conti 1976, Willis 1980). The WR mass loss rates derived by BSW show that in any such evolution the mass loss rate would have to increase and such a change could be expected to be accompanied by a change in the structure and development of the wind. Using published UV Copernicus spectra of ζPup (Morton 1976) we have derived the values k = 1900 km/s and g = -82 km/s/eV for this star. Values of g can now be plotted for an O4f star, the WN7 stars and other WR subclasses in Fig 3b. These data show a trend running from Of-WN7-WR, in line with that that might be expected in the proposed evolutionary scenario.

IUE observations of HD 15570 (O4f) (Willis & Stickland 1980) and SK-65-22 (O6If) (Nandy et al. 1980) show UV spectral characteristics between those of normal Of and WN7 stars and it is postulated that these stars are intermediately evolved objects. Clearly it is of interest to derive values of k and g for their winds to test whether they follow the suggested trend in Fig 3 (their possible location is marked "?" under the heading "O-W"). If such a trend were established it would greatly enhance the hypothesis that these various stellar classes are evolutionary linked.

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