

Ultraviolet observations of stellar winds in Be and ‘normal’ B non-supergiant stars

Raman K. Prinja *Department of Physics and Astronomy, University College
London, Gower Street, London WC1E 6BT*

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Summary. A homogeneous set of wind-velocity and column-density measurements is presented for 40 early-type (B0–B5) Be stars and 40 non-emission, non-supergiant B stars, based on model profile fits to high resolution *IUE* C IV, Si IV and Si III spectra. The characteristics of mass-loss in the Be and ‘normal’ B stars are compared, and related to the wind properties of O type stars.

Stellar winds are evident in Be stars in our sample as late as B3 in C IV, Si IV and/or Si III. Weaker, superionized winds are also present in the most luminous ‘normal’ B stars. Discrete absorption components are apparent in more than 50 per cent of the Be stars in the sample, and their total ionic column density may be ≥ 70 per cent of that due to the ‘underlying’ winds. Maximum observed wind velocities of up to $\sim 1500 \text{ km s}^{-1}$ are evident in Be stars, and are correlated with the projected rotation velocity. The corresponding ratios of maximum observed wind velocity to photospheric escape velocity increase as a function of effective temperature. The ‘normal’ B stars have wind velocities which do not, in general, exceed the photospheric escape velocity. The product of mass-loss rate and ion fraction ($\dot{M}q_i$) is a strong function of stellar luminosity for C³⁺ and Si³⁺ in Be stars; however, the slope of this dependence may be shallower than that noted for O type stars. These results highlight the role of radiation pressure driving in Be star winds, though additional mechanisms may provide the initial acceleration in cooler stars. The relative wind ion fractions and the UV photospheric absorption lines of Be and ‘normal’ B stars are also compared.

1 Introduction

The ‘classical’ definition of a Be star is a non-supergiant B-type star whose spectrum shows emission in one or more of the Balmer lines (see e.g. Jaschek, Slettebak & Jaschek 1981; Collins 1987). These stars generally have large projected rotation velocities, and exhibit remarkably rich properties in many spectral regions, including not just strong Balmer emission, but also large IR excesses, linear polarization and broad shortward-shifted UV (stellar wind) line profiles. In addition, some of these properties may vary on time-scales of $\sim$ hours to years

(see e.g. the proceedings edited by Slettebak 1976; Jaschek & Groth 1982; Slettebak & Snow 1987).

Extensive, quantitative observational descriptions of these characteristics are an essential prerequisite to any detailed physical models of the Be phenomenon. The aim of this paper, therefore, is to concentrate on one aspect associated with the phenomenon; namely, the nature of mass-loss and winds in Be stars. UV spectroscopy, which reveals P Cygni profiles in a variety of resonance lines, provides the most sensitive diagnostic of hot star winds. Recent UV surveys of mass-loss from Be stars have demonstrated the presence of a substantial high-velocity stellar wind, which is not so prominent, for example, in ‘normal’ (non-emission) B stars of the same spectral type and luminosity (see e.g. Snow 1981; Marlborough & Peters 1982; Barker & Marlborough 1985; Grady, Bjorkman & Snow 1987 and the recent reviews by Snow & Stalio 1987 and Snow 1987). Intensive monitoring of individual Be stars has revealed substantial variations in the UV wind profiles on time-scales as short as hours (e.g. Henrichs *et al.* 1983; Doazan *et al.* 1985; Grady *et al.* 1987 and Sonneborn *et al.* 1988). Most of these surveys, however, use equivalent width measures to describe the strengths of UV line profiles displaying evidence of a wind and, therefore, cannot quantitatively address questions about the nature of the stellar wind, the relative ionization balance and the extent of mass-loss.

In this study, we carry out detailed line profile fits to the C iv $\lambda\lambda 1548.2, 1550.8$, Si iv $\lambda\lambda 1393.76, 1402.77$ and Si iii $\lambda 1206.51$ lines observed in the high resolution International Ultraviolet Explorer (*IUE*) satellite spectra of 40 early-type (B0–B5) Be stars in order to derive wind velocities and densities. These lines are very sensitive indicators of mass-loss in this spectral range. The corresponding data for 40 ‘normal’ (non-emission) non-supergiant B stars are also modelled for comparison. In particular, the following principal aspects of Be star winds are addressed in this survey:

- (i) The relative contributions of an ‘underlying’ P Cygni wind, (multiple) discrete absorption components and photospheric lines are isolated as constituents making up the broad shortward shifted UV resonance line profile.
- (ii) The driving mechanisms for Be star winds are examined using comparisons between the mass-loss properties of Be stars derived here and those of O type stars where radiation pressure provides the dominant force (from the survey of Howarth & Prinja 1989; hereafter HP89). In addition, the UV spectra of 40 non-supergiant ‘normal’ non-emission B stars are examined to study, for example, the role of stellar rotation in these winds.

The *IUE* dataset and reduction procedures are introduced in Section 2. The adopted fundamental parameters are discussed in Section 3 and profile fitting methods are described in Section 4. Results on stellar wind morphology, velocities, column densities and mass-loss and ionization balance are presented in Section 5, together with descriptions of the properties of discrete absorption components. These UV properties are compared in Section 6 to H α , IR and polarization observations of Be stars, available in the literature. The roles of radiation pressure and rotation in driving the winds of Be stars are discussed in Section 7, together with a comparison of the properties of photospheric lines in Be and ‘normal’ non-supergiant B stars. A summary of principal results is given in Section 8.

2 Observations

2.1 THE *IUE* DATA SET

This study is based on high-resolution ($R=10^4$) *IUE* SWP (short wavelength, $\lambda\lambda 1150\text{--}2050$ Å) spectra, retrieved from the SERC *IUE* archive maintained at the Rutherford

Appleton Laboratory World Data Center. We restrict ourselves to early-type Be stars, which are most likely to exhibit the presence of substantial stellar winds (see e.g. Grady, Bjorkman & Snow 1987). All stars listed by Slettebak (1982) with spectral types B0 to B5 were selected for which high-resolution *IUE* data are available. Excluded here, therefore, are Oe stars (but see HP89), Herbig Ae and Be stars which are usually associated with nebulosity, and B[e] stars which exhibit forbidden lines in their spectra.

The final database, listed in Table 1, consists of 40 Be stars, and we examine in most cases only one (or two) *IUE* spectra per star. The data set is, therefore, not intended to address the extensive variability evident in many Be stars (see Section 1), but serves as an *extensive* survey of mass-loss in these stars. Where possible, the extent of variability is sampled by examining the two *IUE* spectra per object cited by Grady, Bjorkman & Snow (1987) which represent cases of maximum and minimum total observed absorption strength in C iv, Si iv and Si iii. Although we present here results derived from modelling the 'maximum' cases only; where appropriate, examples of extensive variability are also indicated. (Note, we refer here only to variability between profiles already exhibiting fairly substantial mass-loss.)

For comparison, 40 non-supergiant 'normal' (non-emission) B stars with spectral types B0 to B5 were also selected from the list of Slettebak *et al.* (1975). Apart from ensuring a similar distribution of spectral types to the Be star sample, no specific selection criteria (for example, with respect to projected rotation velocity) were used, other than the requirement for a well exposed high-resolution *IUE* spectrum being available in the data archive. The sample stars, and corresponding *IUE* image numbers, are listed in Table 2.

2.2 DATA REDUCTION

All the spectra were extracted in a uniform manner from the photometrically linearized images provided by the *IUE* ground stations, using the IUEDR software (Giddings 1983a,b) available on the SERC's STARLINK network of VAX computers. The data reduction procedures were identical to those described in detail (for example) by Prinja & Howarth (1986) and HP89. The spectral analysis and data manipulation were carried out interactively using STARLINK software (DIPSO; Howarth & Murray 1987).

The spectra were aligned using strong interstellar lines which were assumed to be at rest wavelength. The observed C iv, Si iv and Si iii profiles were rectified to local continuum levels by fitting cubic polynomials through all points within narrow windows selected as being relatively free of photospheric absorption lines. The Si iii λ 1206.51 profiles were corrected for the effects of the wings of the interstellar Ly α λ 1215.67 absorption by fitting the latter with fully damped theoretical profiles (DIPSO).

3 Stellar parameters

There is currently little *direct* information available about the fundamental photospheric parameters of the Be stars. Interpretation of the meagre information available is complicated, however, as a result of envelope effects and shape distortions due to rapid rotation (see e.g. Slettebak 1987). We assume here, therefore, that the underlying Be star has the same physical characteristics as a 'normal' non-emission B type star of similar spectral type, but acknowledge that, in reality, envelope and rotation effects in Be stars may result in systematic differences in the fundamental parameters.

The spectroscopic MK classifications of Slettebak (1982) and Slettebak *et al.* (1975) are adopted for the Be (Table 1) and 'normal' B stars (Table 2), respectively. We adopt the B star temperature scale of Waters, Côté & Lamers (1987) which is consistent with the O star scale

Table 1. The Be star sample and corresponding adopted physical parameters.

HD	Sp. Type	SWP	T_{eff} (K)	$\frac{L_{\star}}{L_{\odot}}$ (dex)	$\frac{R_{\star}}{R_{\odot}}$	$\frac{M_{\star}}{M_{\odot}}$	$v_e \sin(i)$ (km/s)	v_{esc} (km/s)
5394	B0.5 IVe	8724	29000	4.74	8.2	14	230	765
58978	B0.5 IVe	15957	29000	4.74	8.2	14	280	765
180968	B0.5 IVe	18364	29000	4.74	8.2	14	330	765
110432	B1 IIIe	28004	25000	4.62	8.6	16	300	810
212571	B1 III-IVe	2784	26000	4.58	7.7	13	300	770
63462	B1 IVe	20838	27000	4.54	6.8	10	320	715
28497	B1 Ve	18944	27000	4.38	6.8	10	230	725
35439	B1 Ve	21910	27000	4.38	6.8	10	320	725
200310	B1 Ve	19939	27000	4.38	6.8	10	300	725
52918	B1.5 IIIe	21913	23500	4.66	7.7	20	270	965
44458	B1.5 IVe	21917	24000	4.26	6.3	14	200	905
68980	B1.5 IVe	22119	24000	4.26	6.3	14	115	905
148184	B1.5 Ve	15059	24000	4.06	6.3	14	140	910
33328	B2 III(e)p	21493	17500	4.02	8.8	16	220	825
48917	B2 IIIe	29371	17500	4.02	8.8	16	200	825
113120	B2 IIIe	21155	17500	4.02	8.8	16	300	825
50013	B2 IVe	15029	20000	3.98	6.0	10	220	785
54309	B2 IVe	29373	20000	3.98	6.0	10	200	785
88661	B2 IVe	14434	20000	3.98	6.0	10	220	785
105435	B2 IVe	15961	20000	3.98	6.0	10	220	785
120324	B2 IV-Ve	15962	20000	3.82	6.0	10	155	790
164284	B2 IV-Ve	17975	20000	3.82	6.0	10	240	790
30076	B2 Ve	20844	20000	3.70	6.0	10	180	790
208682	B2 Ve	29403	20000	3.70	6.0	10	250	790
157042	B2.5 IVe	28114	19000	3.78	5.2	10	320	845
56139	B2.5 Ve	15028	19000	3.50	5.2	10	80	850
75311	B2.5 V(e)	22098	19000	3.50	5.2	10	240	850
167128	B3 III(e)	31220	15000	3.62	7.0	13	50	840
142983	B3 IV : e-sh	28613	18000	3.62	5.1	9	400	815
217050	B3 IV : e-sh	19323	18000	3.62	5.1	9	300	815
32991	B3 Ve	21490	18000	3.34	5.1	9	200	820
32343	B3 Ve	5927	18000	3.34	5.1	9	100	820
58343	B3 Ve	21914	18000	3.34	5.1	9	40	820
25940	B4 Ve	24013	16000	3.10	4.7	7	200	750
91465	B4 Ve	21689	16000	3.10	4.7	7	250	750
124367	B4 Ve	26126	16000	3.10	4.7	7	300	750
22192	B5 IIIe-sh	15513	13500	3.18	5.2	8	280	765
109387	B5 IIIe	20985	13500	3.18	5.2	8	200	765
112091	B5 Ve	26125	15000	2.86	4.7	6	220	695
217891	B5 Ve	15935	15000	2.86	4.7	6	100	695

Table 2. The 'normal' (non-emission) B non-supergiant sample and corresponding adopted physical parameters.

HD	Sp Type	SWP	T_{eff} (K)	$\frac{L_*}{L_{\odot}}$ (dex)	$\frac{R_*}{R_{\odot}}$	$\frac{M_*}{M_{\odot}}$	$v_e \sin(i)$ (km/s)	v_{esc} (km/s)
149438	B0 V	28634	31000	4.74	10.0	17	10	770
36512	B0 V	8084	31000	4.74	10.0	17	15	770
143275	B0.3 IV	17395	30000	4.86	9.0	16	150	770
24760	B0.5 III	24381	27500	4.82	10.2	22	130	870
111123	B0.5 III	14931	27500	4.82	10.2	22	35	870
42933	B0.5 IV	2497	29000	4.74	8.2	14	170	760
93030	B0.5 V	11298	29000	4.54	8.2	14	130	780
118716	B1 III	5707	25000	4.62	8.6	16	110	810
122451	B1 III	4520	25000	4.62	8.6	16	70	810
37018	B1 V	20782	27000	4.38	6.8	10	10	725
74575	B1.5 III	5145	23500	4.66	7.7	20	15	965
129056	B1.5 III	4574	23500	4.66	7.7	20	15	965
160578	B1.5 III	4348	23500	4.66	7.7	20	90	965
136298	B1.5 IV	16778	24000	4.26	6.3	14	170	905
151890	B1.5 IV	5879	24000	4.26	6.3	14	190	905
127381	B2 III	22094	17500	4.02	8.8	16	60	825
132058	B2 III	16775	17500	4.02	8.8	16	100	825
3360	B2 IV	28627	20000	3.98	6.0	10	10	785
106490	B2 IV	21954	20000	3.98	6.0	10	140	785
16582	B2 IV	4483	20000	3.98	6.0	10	10	785
121743	B2 IV	21956	20000	3.98	6.0	10	80	785
132200	B2 IV	17459	20000	3.98	6.0	10	10	785
118079	B2 V	20359	20000	3.70	6.0	10	160	790
148605	B2 V	9222	20000	3.70	6.0	10	180	790
44402	B2.5 IV	22111	19000	3.78	5.2	10	30	850
125238	B2.5 IV	20891	19000	3.78	5.2	10	195	850
144294	B2.5 V	22090	19000	3.50	5.2	10	270	850
193924	B2.5 V	21356	19000	3.50	5.2	10	15	850
65575	B3 IV	21952	18000	3.62	5.1	9	50	815
74195	B3 IV	21415	18000	3.62	5.1	9	10	815
32630	B3 V	18720	18000	3.34	5.1	9	100	820
41753	B3 V	9934	18000	3.34	5.1	9	40	820
116087	B3 V	20791	18000	3.34	5.1	9	190	820
45813	B4 V	20783	16000	3.10	5.1	7	110	720
136664	B4 V	20789	16000	3.10	5.1	7	155	720
22928	B5 III	20604	13500	3.18	5.2	8	200	765
15371	B5 IV	21046	15000	3.14	4.7	6	10	695
98718	B5 V	20793	15000	2.86	4.7	6	280	695
128345	B5 V	20786	15000	2.86	4.7	6	155	695
106911	B5 V	21957	15000	2.86	4.7	6	220	695

used by HP89. Be and ‘normal’ non-supergiant B star luminosities in Tables 1 and 2 are derived using absolute magnitudes (versus spectral type) from Carnochan (1982), bolometric corrections (as a function of effective temperature) from Buser & Kurucz (1978), together with the relation

$$\log(L_*/L_\odot) = -0.4(M_{\text{BOL}} - 4.75).$$

Some Be star luminosities based on open cluster membership and double star systems (see e.g. Mermilliod 1982, and references in Slettebak 1987) suggest that certain Be stars may lie up to two magnitudes above the zero age main sequence. Collins & Sonneborn (1977) point out, however, that the interpretation of these data is complicated by the effects of rapid rotation, which will move that star to the right in a colour–magnitude diagram (toward the giant region).

For both data sets we use the radii (of non-supergiant B stars) given in Underhill & Doazan (1982), which are compiled from data on eclipsing, double-lined spectroscopic binaries, and from angular diameters and distances (e.g. Underhill *et al.* 1979). The stellar masses available for ‘normal’ B-type stars, as reviewed in Popper (1980) and summarized in Underhill & Doazan (1982), are also adopted in Tables 1 and 2 for the Be and non-emission B stars. Finally, also listed in Tables 1 and 2 are the projected rotation velocities, $v_e \sin(i)$, from Slettebak (1982) and Slettebak *et al.* (1975) respectively, together with photospheric escape velocities, v_{esc} , which have been corrected for electron scattering radiation pressure but not for rapid rotation.

4 Profile fitting

4.1 ‘UNDERLYING’ P Cygni PROFILE

One of the principal aims of this study is to model the UV resonance line profiles in order to establish an extensive database of Be star wind velocities and column densities for both the ‘underlying’ P Cygni wind and discrete absorption components.

The procedures adopted for profile fitting are now extensively documented in our recent O star studies (see e.g. Prinja & Howarth 1986; Prinja, Howarth & Henrichs 1987; HP89). The basic assumptions particularly worth stressing here are those of isotropic scattering and a spherical symmetric, non-rotating extended atmosphere; we acknowledge, of course, that the latter especially may be a poor approximation in the case of Be stars (see e.g. Marlborough 1987).

Briefly, where relevant, a Sobolev code is used (see Howarth 1984; the velocities quoted here are still highly supersonic) to compute model P Cygni profiles, parameterized by a velocity law of the form

$$w(r) = v(r)/v_* = (1 - R_*/r)^\beta, \quad (1)$$

and by an optical depth as a function of velocity

$$\tau(w) = \tau_0 z (1 - w/z)^\gamma, \quad (2)$$

where v_* is the maximum velocity observed in absorption in any line (*cf.* HP89), and $z = v_{\text{edge}}/v_*$, where v_{edge} is the maximum velocity displacement in the line being modelled. It is important to note that in stars with weak winds the outer parts of the flow are not opaque enough to reveal themselves in the observed UV lines. Therefore, in these cases, v_* may underestimate the terminal or ‘far-field’ velocity of the winds. The variables τ_0 and γ are free parameters. A value of $\beta = 1$ was adopted as a reasonable representation of the time-averaged hot star wind velocity law (e.g. Pauldrach, Puls & Kudritzki 1986; Friend & Abbott 1986; Bertout *et al.*

1985). Within the constraints of the Sobolev modelling, the calculated profiles are matched only to the absorption parts of the observed resonance lines, and these data do not in themselves provide sufficient quantitative information to warrant modifications in the value of β .

4.1.1 Absorption due to photospheric lines

Before these models can realistically be matched to the observed UV resonance lines, some allowance must be made for the contribution to the profile of numerous (often strong) photospheric lines (see e.g. Hubený, Harmanec & Stefl 1986). In the absence of appropriate non-LTE synthesized spectra, the approximation we adopt in modelling the C iv $\lambda\lambda$ 1548.19, 1550.76 and Si iv $\lambda\lambda$ 1393.76, 1402.77 resonance doublets is to incorporate explicitly, as a lower boundary to the Sobolev calculation, the observed *IUE* photospheric spectra of selected 'standard' stars of similar spectral type to the candidate star. The 'standard' stars used to model the C iv and Si iv profiles in the Be and B stars are listed in Table 3 and were selected as showing no observational evidence for the presence of a stellar wind in the *IUE* spectra examined. They were regarded as appropriate provided they matched well the observed photospheric spectra straddling the wind resonance lines of the star being modelled. Differences between the rotational velocities of the 'standard' and candidate stars were approximately accounted for by convolving the former with a rotational broadening function (see e.g. Prinja & Howarth 1986).

The poor sensitivity of *IUE* data at short wavelengths and the highly variable nature of Si iii λ 1206.51 photospheric spectra in B stars make the technique described above inappropriate for modelling the (often weak) stellar wind profiles in Si iii. To model this line, therefore, we followed the procedures outlined by Snow (1981) and, within the optically thin approximation, folded (at line centre) the long wavelength side of the observed *IUE* profile on to the shortward wing. The resulting (symmetrical) profile was assumed to be an appropriate approximation to the underlying photospheric spectra, and was incorporated as a lower boundary to the Sobolev calculation.

Results of P Cygni profile fits to the observed C iv, Si iv and Si iii lines of Be and 'normal' non-supergiant B stars are presented in Tables 4 and 5, respectively, and some examples are shown in Fig. 1.

The total ionic column density in the 'underlying' profile, N_i^P (Tables 4 and 5), between $w=0$ and 1 may be obtained by combining the Sobolev optical depth, as a function of velocity,

$$\tau(v) = \frac{\pi e^2}{m_e c} f \lambda_0 n_i(r) \left(\frac{dv}{dr} \right)^{-1},$$

Table 3. List of the photospheric 'standard' stars adopted.

Be stars:	Range	Photospheric 'standard'	Sp. Type	SWP
	B0.5 IVe – B1.5 Ve	HD 148184	B1.5 Ve	15059
	B2 IIIe – B2.5 Ve	HD 50013	B2 IVe	15029
	B3 IIIe – B5 Ve	HD 58343	B3 Ve	21914
'Normal' B stars:				
	B0 V – B2 IV	HD 37018	B1 V	20782
	B2 V – B3 V	HD 3360	B2 IV	28627
	B4 V – B5 V	HD 15371	B5 IV	21046

Table 4. Model profile fits to P Cygni profiles in Be stars. a.aa(bb) means $a.aa \times 10^{bb}$.

HD	v_* (km s^{-1})	C IV				Si IV				Si III			
		z	τ_0	γ	N^P (cm^{-2})	z	τ_0	γ	N^P (cm^{-2})	z	τ_0	γ	N^P (cm^{-2})
5394	1500	1.00	0.8	0.8	8.36(14)	...	...	...	...	...	...	...	...
58978	1100	1.00	1.7	0.7	1.38(15)	0.86	2.0	1.0	4.17(14)	0.59	10.0	3.0	1.80(14)
180968	1350	1.00	3.5	1.0	2.96(15)	0.89	1.7	1.0	4.65(14)	0.63	10.0	1.3	4.38(14)
110432	1450	1.00	3.0	1.0	2.73(15)	0.92	1.5	1.0	4.71(14)	0.50	5.0	1.5	1.36(14)
212571	850	1.00	2.0	1.0	1.07(15)	0.94	2.2	1.0	4.23(14)	0.76	5.0	2.0	1.54(14)
63462	1350	1.00	2.5	1.0	2.12(15)	0.90	1.0	1.0	2.80(14)	0.53	0.5	1.0	1.78(13)
28497	1000	1.00	2.2	1.0	1.38(15)	0.95	1.7	1.0	3.93(14)	0.95	3.0	1.0	2.55(14)
35439	1000	1.00	2.0	1.0	1.25(15)	0.73	2.3	1.0	3.14(14)	0.87	2.2	1.0	1.57(14)
200310	1050	1.00	1.6	1.0	1.05(15)	0.90	1.5	1.0	3.27(14)	0.90	2.5	1.5	1.60(14)
52918	1050	1.00	2.0	1.0	1.32(15)	1.00	1.8	1.0	4.84(14)	0.97	1.5	1.0	1.39(14)
44458	700	1.00	1.8	1.0	7.90(14)	1.00	0.7	1.0	1.25(14)	0.93	5.0	2.0	1.90(14)
68980	850	...	...	...	...	...	...	...	...	1.00	0.5	0.5	5.33(13)
148184	...	...	...	...	...	...	...	...	...	...	...	...	...
33328	1100	1.00	0.8	1.0	5.52(14)	0.91	0.5	1.5	9.33(13)	1.00	0.5	0.5	6.90(13)
48917	1000	1.00	2.0	0.8	1.39(15)	0.85	2.4	1.0	4.44(14)	0.95	2.0	0.6	2.12(14)
113120	1050	1.00	1.6	0.7	1.24(15)	...	...	...	...	0.48	0.7	1.0	1.59(13)
50013	...	...	...	...	...	...	...	...	...	...	...	...	...
54309	850	...	...	...	...	...	...	...	...	1.00	0.5	0.5	5.33(13)
88661	930	...	...	...	...	...	...	...	...	1.00	0.7	1.0	6.12(13)
105435	850	...	...	...	...	...	...	...	...	1.00	0.5	0.5	5.33(13)

Table 4 – continued

HD	v_* (km s ⁻¹)	C IV			Si IV			Si III		
		z	τ_0	γ	N^P (cm ⁻²)	z	τ_0	γ	N^P (cm ⁻²)	N^P (cm ⁻²)
120324	800	...	...	...	...	...	...	0.4	0.5	4.01(13)
164284	720	...	...	...	...	...	...	...	...	...
30076	825	1.00	2.0	1.0	1.03(15)	1.00	2.7	2.5	3.26(14)	1.83(14)
208682	650	1.00	1.5	1.0	6.11(14)	1.00	2.5	1.5	3.33(14)	2.20(14)
157042	830	0.84	1.8	1.0	6.61(14)	0.84	2.0	1.0	3.00(14)	1.25(14)
56139	600	1.00	0.4	1.3	1.31(14)	...	...	...	...	6.02(13)
75311	780	...	...	...	...	...	...	...	...	7.34(13)
167128	650	1.00	0.5	1.0	2.04(14)	0.80	0.7	1.0	7.45(13)	1.08(14)
142983	...	...	...	...	...	...	...	...	...	...
217050	...	...	...	...	...	...	...	...	...	...
32991	700	...	...	...	...	1.00	0.7	1.0	1.25(14)	...
32343	...	...	...	...	...	...	...	...	...	...
58343	...	...	...	...	...	...	...	...	...	...
25940	...	...	...	...	...	...	...	...	...	...
91465	270	...	...	...	...	...	...	...	...	...
124367	...	...	...	...	...	...	...	...	...	...
22192	270	...	...	...	...	...	...	...	...	...
109387	...	...	...	...	...	...	...	...	...	...
112091	...	...	...	...	...	...	...	...	...	...
217891	...	...	...	...	...	...	...	...	...	...

Table 5. Model profile fits to P Cygni profiles in 'normal' B non-supergiant stars. No stellar winds are evident in our sample for the later type-B stars in Table 2 (HD 121743–106991 inclusive). a.aa(bb) means $a.aa \times 10^{bb}$.

HD	v_* (km s^{-1})	C IV				Si IV				Si III			
		z	τ_0	γ	N^P (cm^{-2})	z	τ_0	γ	N^P (cm^{-2})	z	τ_0	γ	N^P (cm^{-2})
149438	1200	1.00	8.0	3.0	3.01(15)	0.60	1.3	1.0	1.44(14)	...	...	...	...
36512	650	1.00	6.0	2.0	1.63(15)	...	...	...	...	...	...	...	...
143275	800	1.00	1.5	1.5	6.02(14)	...	...	...	...	...	...	...	...
24760	500	0.55	1.6	1.0	1.52(14)	1.00	0.4	1.0	5.12(13)	...	...	...	...
111123	420	1.00	2.0	1.0	5.27(14)	0.88	0.8	1.0	6.66(13)	...	...	...	...
42933	380	1.00	0.7	1.0	1.67(14)	...	...	...	...	...	...	...	...
93030	...	...	...	...	...	...	...	...	...	...	...	...	...
118716	650	0.64	0.5	1.0	8.35(13)	1.00	0.4	1.0	6.66(13)	...	...	...	...
122451	950	1.00	1.0	1.8	4.26(14)	0.68	0.4	1.0	4.50(13)	...	...	...	...
37018	...	...	...	...	...	...	...	...	...	...	...	...	...
74575	520	0.96	1.0	1.0	3.01(14)	1.00	0.6	1.0	7.99(13)	...	...	...	...
129056	700	1.00	1.5	1.5	5.27(14)	1.00	0.7	1.0	1.25(14)	0.93	1.0	1.0	5.69(13)
160578	600	0.78	0.5	1.0	1.14(14)	1.00	0.4	1.0	6.14(13)	...	...	...	...
136298	...	...	...	...	...	...	...	...	...	...	...	...	...
151890	630	...	...	...	...	...	...	...	...	1.00	0.3	0.4	2.54(13)
127381	...	...	...	...	...	...	...	...	...	...	...	...	...
132058	...	...	...	...	...	...	...	...	...	...	...	...	...
3360	...	...	...	...	...	...	...	...	...	...	...	...	...
106490	630	...	...	...	...	...	...	...	...	1.00	0.2	0.4	1.69(13)
16582	500	...	...	...	...	...	...	...	...	1.00	0.5	1.0	2.35(13)

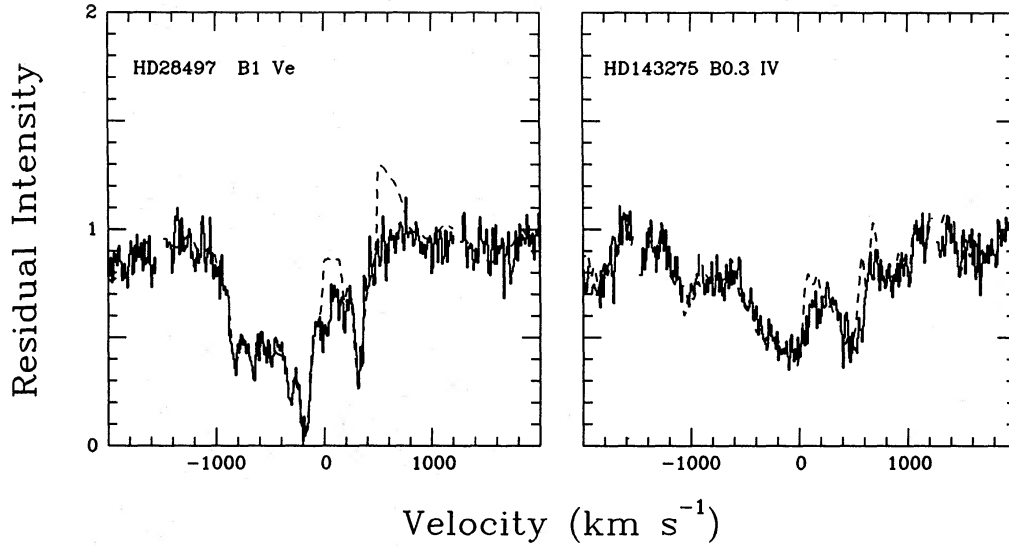


Figure 1. Examples of model profile fits (dashed lines) to 'underlying' P Cygni profiles in the C iv $\lambda\lambda 1548.2, 1550.8$ spectra. Multiple discrete absorption components are also modelled in the case of HD 28497.

with equation 2 to give

$$N_i^P(0, 1) = \frac{\tau_0 z^2 v_*}{f \lambda_0} \frac{m_e c}{\pi e^2} \frac{(1 - w/z)^\gamma}{\gamma + 1}, \quad (3)$$

where f is the transition oscillator strength, λ_0 is the rest wavelength and $n_i(r)$ is the ionic number density (see e.g. HP89).

4.2 DISCRETE ABSORPTION COMPONENTS

Where appropriate, and after matching any 'underlying' P Cygni profile, excess absorption present in the form of well-defined discrete (narrow) absorption components was modelled (Howarth 1987) assuming a Gaussian opacity distribution for the absorbing material (see e.g. Henrichs *et al.* 1983 and Prinja & Howarth 1986). Note, therefore, that (for convenience) the discrete components are not treated as being radiatively coupled with the 'underlying' wind; although, of course, we acknowledge that they are an integral part of the stellar wind. The empirical techniques used here primarily provide a consistent and objective means of estimating the velocities and strengths of the discrete components, and we do not imply here any specific physical model for their formation. (Other empirical methods would yield comparable values for these parameters, see e.g. Prinja & Howarth 1985.)

The observed rectified discrete component spectrum is thus represented by

$$I(v) = \prod \left[\exp \left\{ -\tau_c \exp \left[-\left(\frac{v - v_c}{v_t} \right)^2 \right] \right\} \right], \quad (4)$$

where $I(v)$ is the residual intensity in the quotient spectrum, and the product is over doublets (where appropriate) and all identifiable features. The optical depth at line centre (τ_c), the velocity displacement (v_c) and the broadening parameter (v_t) are the free parameters in a least squares fit of this equation. For the C iv and Si iv doublets, τ_c was constrained in the ratio $(\lambda_0 f)_1 / (\lambda_0 f)_2$. We estimate realistic errors to be $\sim 20 \text{ km s}^{-1}$ for v_c and v_t , and $\sim 10 - 20$ per cent in τ_c .

Table 6. Model profile fits to discrete absorption components in Be stars. a.aa(bb) means $a.aa \times 10^{bb}$.

HD	C IV				Si IV				Si III			
	v_c (km s ⁻¹)	$\log(\tau_c)$	v_t (km s ⁻¹)	N^N (cm ⁻²)	v_c (km s ⁻¹)	$\log(\tau_c)$	v_t (km s ⁻¹)	N^N (cm ⁻²)	v_c (km s ⁻¹)	$\log(\tau_c)$	v_t (km s ⁻¹)	N^N (cm ⁻²)
5394	-1357	+0.020	36	8.41(13)	...	...	...	...	...	...	...	...
58978	-420	+0.253	42	1.68(14)	...	...	...	...	...	...	...	...
	-334	+0.208	24	8.63(13)	...	...	...	...	...	...	...	...
	-183	+0.488	109	7.46(14)	-161	+0.187	123	1.72(14)	...	...	...	...
180968	-633	+0.053	79	1.99(14)	-570	-0.033	81	6.82(13)	...	...	...	...
	...	...	...	...	-219	+0.515	147	4.37(14)	...	...	...	...
110432	-1008	-0.018	125	2.68(14)	-995	+0.067	165	1.75(14)	...	...	...	...
	-619	+0.182	124	4.20(14)	-559	+0.171	158	2.13(14)	...	...	...	...
	-383	+0.577	116	9.76(14)	-356	+0.275	96	1.64(14)	...	...	...	...
212571	-579	-0.602	97	5.41(13)	...	...	...	...	-382	+0.548	44	5.19(13)
	-326	+0.180	95	3.20(14)	-324	-0.116	38	2.64(13)	-566	-0.442	44	5.31(12)
63462	...	...	...	...	-184	+0.405	71	1.64(14)	-338	-0.047	24	7.18(12)
	-604	-0.298	54	6.05(13)	...	...	...	...	...	...	...	...
	-395	+0.512	102	7.39(14)	...	...	...	...	...	...	...	...
28497	-158	-0.167	70	1.22(14)	...	...	...	...	...	...	...	...
	-825	-0.225	44	5.84(13)	...	...	...	...	-815	-0.305	42	6.96(12)
	-659	-0.194	27	3.85(13)	...	...	...	...	-656	-0.391	55	7.48(12)
	-311	-0.155	16	2.49(13)	...	...	...	...	-316	+0.359	47	3.58(13)
35439	-184	+0.302	45	2.01(14)	-164	+0.347	80	1.61(14)	-171	+0.284	53	3.40(13)
	-289	-0.211	65	8.89(13)	-271	-0.332	43	1.82(13)	...	...	...	...
	-137	+0.422	67	3.93(14)	-130	+0.366	68	1.44(14)	...	...	...	...
200310	-435	-0.295	47	5.30(13)	...	...	...	...	...	...	...	...
	-295	+0.479	55	3.69(14)	-257	-0.219	73	4.00(13)	...	...	...	...
	-171	+0.507	47	3.36(14)	-169	-0.100	39	2.81(13)	...	...	...	...
52918	-945	-0.243	50	6.37(13)	-954	-0.440	38	1.26(13)	...	...	34	4.67(12)
	-801	-0.313	26	2.82(13)	-790	-0.300	80	3.65(13)	-929	-0.386	...	...
44458	-339	-0.422	94	7.92(13)	-315	-0.366	42	1.64(13)	...	...	...	...
	-102	+0.199	116	4.08(14)	...	...	...	...	...	...	...	...

Table 6 – continued

HD	C IV				Si IV				Si III			
	v_c (km s ⁻¹)	$\log(\tau_c)$	v_t (km s ⁻¹)	N^N (cm ⁻²)	v_c (km s ⁻¹)	$\log(\tau_c)$	v_t (km s ⁻¹)	N^N (cm ⁻²)	v_c (km s ⁻¹)	$\log(\tau_c)$	v_t (km s ⁻¹)	N^N (cm ⁻²)
33328	-941	-0.080	86	1.60(14)	-917	-0.588	63	1.48(13)	-956	-0.120	22	5.58(12)
48917	-784	-0.551	90	5.65(13)	...	...	...	...	...	...	...	...
	-543	+0.035	78	1.88(14)	-575	-0.482	54	1.62(13)	...	...	...	...
	-336	+0.268	83	3.42(14)	-346	-0.088	65	4.82(13)	...	...	...	...
	-200	+0.451	35	2.20(14)	-219	+0.460	33	6.64(13)	-213	+0.532	43	4.88(13)
113120	-928	-0.520	64	4.31(13)	...	...	...	...	...	...	...	...
	-789	-0.373	39	3.68(13)	...	...	...	...	...	...	...	...
	-623	+0.094	90	2.49(14)	...	...	...	...	...	...	...	...
54309	-967	-0.293	52	5.91(13)	...	...	...	...	...	...	...	...
	-289	-0.556	82	5.07(13)	...	...	...	...	...	...	...	...
	-145	-0.403	43	3.78(13)	...	...	...	...	...	...	...	...
88661	-862	-0.332	47	4.87(13)	...	...	...	...	...	...	...	...
164284	-723	-0.182	60	8.80(13)	...	...	...	...	...	...	...	...
	-610	-0.059	71	1.38(14)	-593	-0.413	87	3.06(13)	-599	+0.051	32	1.20(13)
	-458	+0.122	89	2.62(14)	-415	+0.040	89	8.86(13)	-446	+0.280	54	3.44(13)
	-291	+0.133	79	2.39(14)	-265	-0.106	34	2.42(13)	-274	+0.552	44	5.23(13)
	-162	+0.359	33	1.68(14)	-175	+0.360	25	5.20(13)	-172	+0.285	36	2.32(13)
30076	-625	-0.376	102	9.57(13)	-579	-0.491	33	9.68(12)	...	...	...	...
	-199	+0.147	77	2.40(14)	-167	+0.285	22	3.85(13)	...	...	...	...
208682	-153	-0.057	25	4.88(13)	-159	-0.286	31	1.46(13)	...	...	...	...
157042	-603	-0.518	35	2.37(13)	...	...	...	...	...	...	...	...
	-432	-0.483	79	5.78(13)	...	...	...	...	...	...	...	...
	-312	-0.510	24	1.65(13)	...	...	...	...	...	...	...	...
	-146	-0.177	82	1.21(14)	...	...	...	...	...	...	...	...
32991	-724	-0.519	42	2.83(13)	...	...	...	...	...	...	...	...
	-493	-0.016	129	2.77(14)	...	...	...	...	...	...	...	...
91465	-273	-0.260	102	1.25(14)	-260	-0.166	94	5.83(13)	-213	+0.532	43	4.88(13)
	-71	-0.051	76	1.50(14)	-83	+0.082	100	1.10(14)	-84	+0.444	50	4.63(13)
22192	-272	-0.533	65	4.24(13)	...	...	...	...	...	...	...	...

The column density in the discrete absorption components (N_i^N) is given by

$$N_i^N = \frac{\sqrt{\pi}}{\pi e^2 / m_e c} \frac{1}{\lambda_0 f (1 + v_c/c)} \tau_c v_i, \quad (5)$$

(Henrichs *et al.* 1983). The discrete component parameters are presented in Table 6. Because the Sobolev model of the ‘underlying’ P Cygni profiles breaks down at (or near) zero velocity resulting in a poor match to the data, we cannot model discrete components which reside very close to the rest velocity. In addition, the poor data quality and singlet nature of Si III makes discrete component identification very uncertain in this line. Thus, we model here only those discrete components in Si III which are also identified (at that velocity) in the C IV and/or Si IV doublets. (It is now a well established property of discrete absorption components in early-type stars that they occur at the same velocity in different ions, e.g. Gathier, Lamers & Snow 1981; Prinja & Howarth 1986.)

5 Results

5.1 STELLAR WIND MORPHOLOGY

5.1.1. Be stars

Comments regarding Be stellar wind UV morphology are complicated by the often highly transient and variable nature of the line profiles (see e.g. Doazan *et al.* 1985, 1989). It is, in fact, one of the remarkable properties of this class of objects that those stars noted in Table 4 as showing no evidence of a wind could ‘switch on’ and display substantial mass-loss over an undetermined time-scale. With this caveat in mind, we offer below some remarks concerning the presence of winds in Be stars based on our limited data set of 40 B0–B5 stars:

(i) The C IV $\lambda\lambda$ 1548.2, 1550.8 resonance doublet is clearly a sensitive indicator of mass-loss in the early-type Be stars (Fig. 2), as it is, for example, in the O stars (see e.g. HP89). Some of the strongest stellar wind profiles are evident in C IV, taking the form of a well-developed ‘underlying’ P Cygni profile for spectral types as late as B2. (Note, however, that the emission parts of the P Cygni profiles are highly suppressed and are mostly not observed.) Evidence of a wind in stars later than B3 is only in the form of (multiple) discrete absorption components (see also Barker & Marlborough 1985).

(ii) The Si IV $\lambda\lambda$ 1393.76, 1402.77 resonance profiles of Be stars are remarkable because they show evidence of a stellar wind in main-sequence stars (Fig. 2), and, therefore, do not strictly follow the conspicuous luminosity class dependence of Si IV noted by Walborn & Panek (1984) for O-type stars. If one accepts that the appearance of Si IV in the spectra of O, B and Be stars is correlated with luminosity class, then the exceptional presence of a stellar wind in the Si IV spectra of Be main-sequence stars is perhaps consistent with higher mass-loss rates in Be stars relative to corresponding ‘normal’ non-emission B stars (see e.g. HP89). However, the enhanced Si IV line in Be stars may not necessarily imply a higher wind density, for example, if Si⁴⁺ is not the dominant ionization stage.

(iii) Stellar wind signatures, due to P Cygni profile and/or discrete components, are evident (though often weakly) in Si III λ 1206.51 as late as B3 in giants and dwarfs (see Fig. 2 and Table 4). Only the most luminous Be stars (B1 and earlier, $T_{\text{eff}} \geq 27\,000$ K) show evidence of a stellar wind in N V $\lambda\lambda$ 1238.82, 1242.80. The C II $\lambda\lambda$ 1334.53, 1335.71 resonance doublet is difficult to interpret because of the dominant interstellar components. However, line profile variability can provide a very useful indicator of the presence of a stellar wind in C II, and examples are

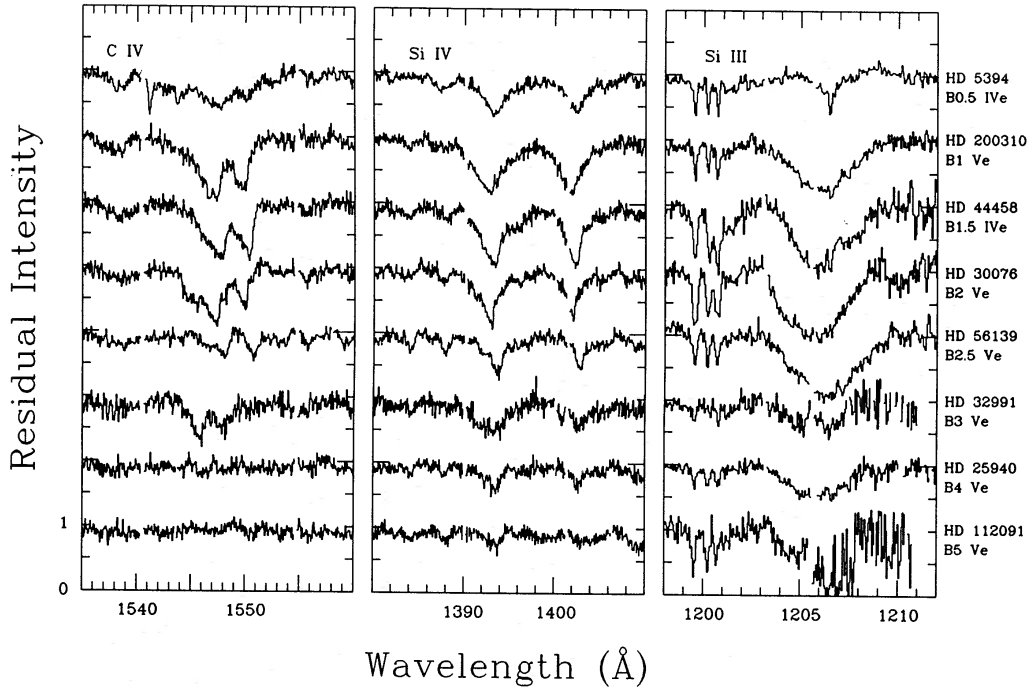


Figure 2. Typical examples of observed *IUE* line profiles of Be stars in our sample. The spectra are labelled with HD numbers and spectral types.

shown in Fig. 3 of cases where absorption enhancements are evident in C II which correlate with corresponding changes in the C IV, Si IV and Si III line profiles.

(iv) This data set cannot quantitatively address the question of whether the progressive variable discrete absorption components seen in O-type stars (see e.g. Prinja & Howarth 1988) represent the same basic phenomenon as discrete features apparent in Be stars. Some differences in their characteristics may, however, be noted here. First, the degree and extent of multiplicity in the discrete components in Be stars (~ 50 per cent of the stars show more than one feature in a profile) are higher than noted in the 203 O star survey of HP89 (~ 10 per cent). In addition, the discrete (narrow) components in Be stars occur over a much wider range of velocities (down to $\leq 0.2 v_{\text{edge}}$), whereas the features evident in single 'snap shot' spectra of O stars are invariably seen at $\sim 0.8 v_*$. Interestingly, we find six examples of Be stars where the entire wind in C IV, Si IV and Si III is in the form of discrete components only, *without* any clear evidence of an 'underlying' P Cygni-type profile (Fig. 4). This property was never noted, for example, in the O star surveys of Prinja & Howarth (1986) and HP89.

Although some weak or unresolved Be star discrete components may have remained unaccounted for in our modelling (Table 6), the identification of an extended asymmetric shortward wing (interpreted here in terms of an 'underlying' P Cygni profile) is clearly defined in the majority of high resolution *IUE* data examined.

5.1.2 'Normal' non-supergiant B stars

It is already widely recognized that stellar winds are evident in Be stars at spectral types and luminosities where they are not so prominent in corresponding 'normal' non-supergiant B stars (e.g. Grady, Bjorkman & Snow 1987 and references in Snow 1987). Our results are consistent with their observations, and we note the following points.

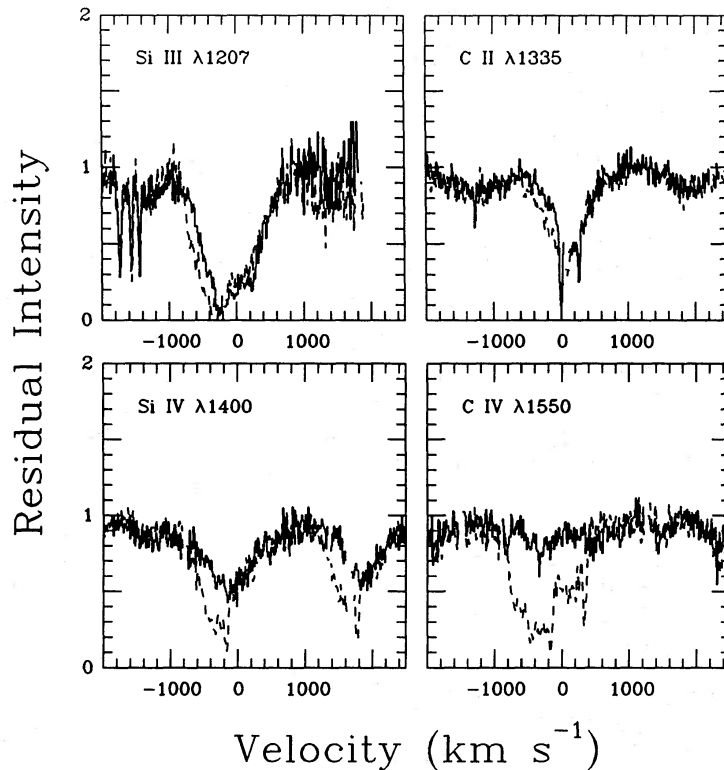


Figure 3. An example of the extensive stellar wind variability evident in HD 164284 (B2 IV – Ve; SWP25653 – solid line; SWP17975 – dashed line).

(i) Superionized winds due to C IV are also apparent in the ‘normal’ B non-supergiant stars down to spectral types B1.5 (see Fig. 5). Such high stages of ionization are not expected at these effective temperatures under conditions of radiative equilibrium (e.g. Lamers & Snow 1978). In addition, some examples of a weak stellar wind may be tentatively noted in Si III at intermediate spectral types (B1.5 and B2; Table 5).

(ii) No line asymmetries, indicating the presence of a stellar wind, are apparent in the Si IV spectra of *main-sequence* B stars in our data set (Table 5 and Fig. 5). Like O stars, and unlike Be stars (Section 5.1.1), winds in the Si IV profiles of ‘normal’ B non-supergiants appear to be confined to giants.

(iii) Discrete absorption components are *not* identified in these non-emission B stars. This result may be a consequence of the weak ‘underlying’ winds evident in these stars if, for example, discrete components in B stars represent a perturbation of the ambient wind (*cf.* O stars, HP89).

5.2 WIND VELOCITIES

The maximum wind velocities observed in absorption in any line (v_*) are listed in Tables 4 and 5 for the Be and ‘normal’ B stars, respectively. HP89 and Prinja, Barlow & Howarth (in preparation) describe in detail the suggestion that v_* may not equal the ‘far field’ (terminal) velocity of the wind, v_∞ , principally as a consequence of wind turbulence and/or non-monotonic velocity laws. In addition, many of the observed profiles of Be and ‘normal’ B stars examined here exhibit only a weak stellar wind, with shallow shortward edges. In these cases the outer parts of the wind are not opaque enough in the observable lines and material in these regions may not be detected.

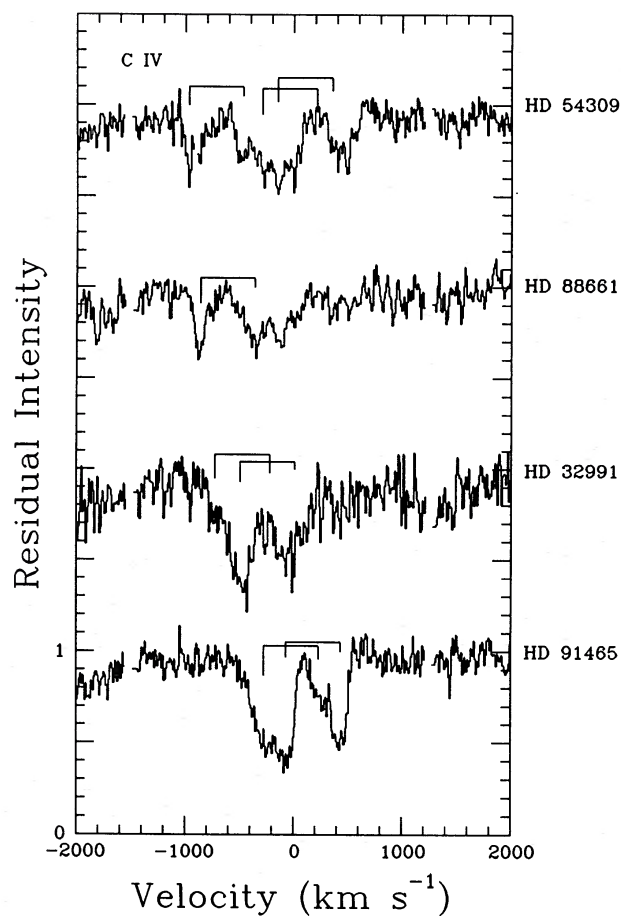


Figure 4. The C IV resonance doublet spectra of Be stars in our sample where evidence for a stellar wind is solely in the form of (multiple) discrete absorption components (whose velocities are indicated).

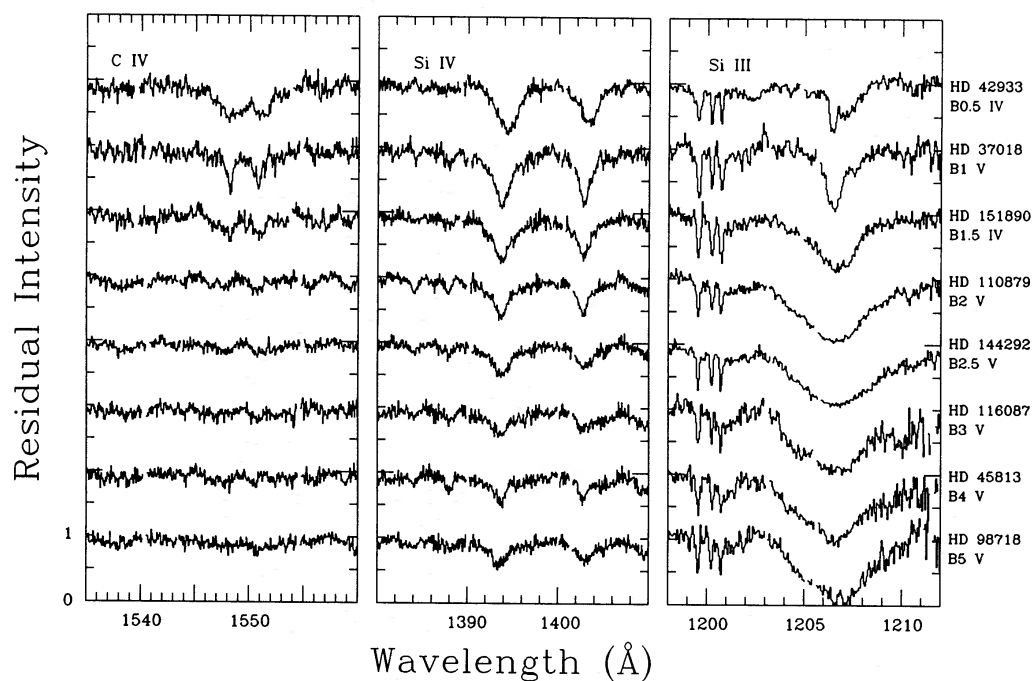


Figure 5. Typical examples of observed IUE line profiles of 'normal' non-supergiant B stars in our sample. The spectra are labelled with HD numbers and spectral types.

5.2.1 The ratio v_*/v_{esc} versus T_{eff}

The results in Table 4 do, however, highlight the presence of high-velocity (up to $\sim 1500 \text{ km s}^{-1}$) winds in Be stars. The recently refined radiation-pressure-driven wind theory (see e.g. Friend & Abbott 1986 and Pauldrach, Puls & Kudritzki 1986) predicts a drop in the ratio of v_*/v_{esc} towards lower effective temperatures, essentially as a result of the greater number of weaker lines driving the B star winds (e.g. compared to O stars where a few very strong lines dominate). The ratio of v_*/v_{esc} (from Tables 5 and 6) is plotted as a function of T_{eff} in Fig. 6(a) for Be and 'normal' non-supergiant B stars. The corresponding O star results from HP89 are also shown. We note the following main points from this figure.

(i) For Be stars hotter than $\sim 20\,000 \text{ K}$ (spectral types B2 and earlier) the maximum observed wind velocities are generally in excess of the escape velocity at the photosphere.

(ii) The ratio of v_*/v_{esc} for Be stars appears to increase as a function of T_{eff} , ranging from ~ 0.4 to 2.0 , and it 'connects' at the hotter end with the bulk of O star values, for which ~ 3.0 is the average. This trend with T_{eff} is in qualitative agreement with line-driven wind theory predictions (e.g. Friend & Abbott 1986).

(iii) No relation is evident between v_*/v_{esc} and T_{eff} for the 'normal' B non-supergiant stars in Fig. 6(a). The majority of these data exhibit much slower winds ($v_* \leq 1000 \text{ km s}^{-1}$), and the maximum observed wind velocities do *not*, in general, exceed the photospheric escape velocities.

5.2.2 The ratio v_*/v_{esc} versus $v_e \sin(i)/v_{\text{crit}}$

The mostly large projected rotation velocities of Be stars have led to interest in the possibility that the stellar winds of these stars may be distorted and enhanced by rapid stellar rotation (see e.g. the review by Marlborough 1987). The ratio of v_*/v_{esc} versus $v_e \sin(i)/v_{\text{crit}}$ is plotted in Fig. 6(b) for the Be and 'normal' B stars. The critical velocity, v_{crit} , is the rotation velocity at which the centrifugal force is equal to gravity [$=v_{\text{isc}}/\sqrt{(2)}$]; thus v_* and $v_e \sin(i)$ in Fig. 6(b) are normalized in the same way.

The data for Be stars, where $v_e \sin(i)/v_{\text{crit}}$ ranges from ~ 0.1 to 0.75 , show a trend of increasing v_*/v_{esc} as a function of $v_e \sin(i)/v_{\text{crit}}$. This apparent relation of the maximum

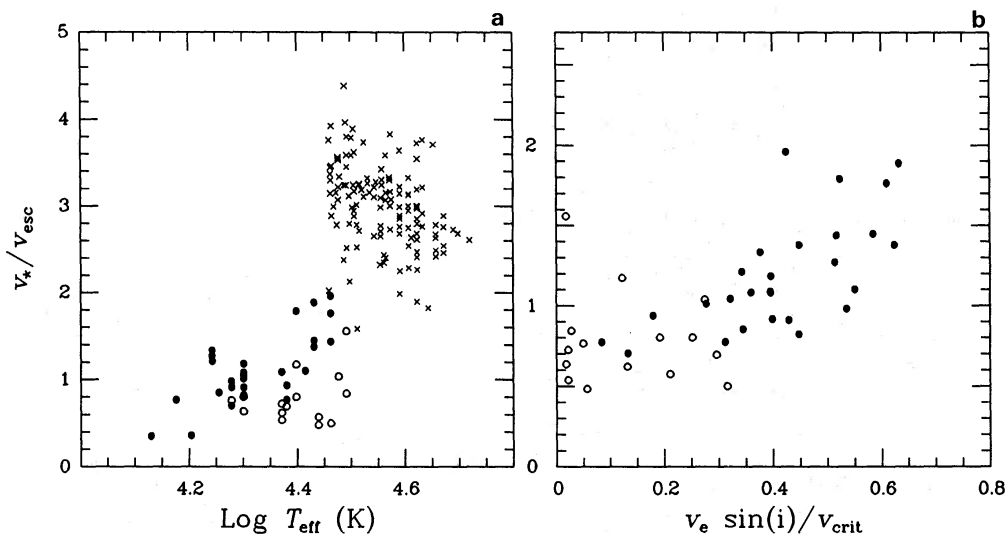


Figure 6. (a) The ratio of v_*/v_{esc} as a function of effective temperature. The filled ($\bullet$) and open ($\circ$) circles are data for Be and 'normal' B stars, respectively. The corresponding O star data from HP89 (crosses) are also shown. (b) The effect of rotation on the maximum observed wind velocities in Be ($\bullet$) and 'normal' B stars ($\circ$).

observed wind velocity of Be stars increasing with the projected stellar rotation velocity is discordant with the (spherically symmetric) line-driven wind theory predictions of Friend & Abbott (1986) and Pauldrach, Puls & Kudritzki (1986), who (with finite disc corrected models) predict a *decrease* in the terminal velocity as a function of rotation velocity. However, Poe & Friend (1986) have calculated models for the structure of a radiation-pressure-driven stellar wind which includes a magnetic field (in addition to the finite disc correction) and have applied it to Be stars. Interestingly, they note that a magnetic field of ~ 100 G forces the terminal velocity to *rise* with increasing rotation velocity. This result may be in qualitative agreement with the correlation presented in Fig. 6(b). (Note, Barker 1987 has reviewed that the current observational lower limit for the detection of magnetic fields in Be stars may be $\geq 10^2$ G depending on field geometry and orientation.)

5.3 WIND DENSITIES

5.3.1 The contribution due to discrete absorption components

Discrete absorption components are evident in more than 50 per cent of the Be stars in our sample (Section 5.1). It is now widely recognized that they are an integral part of the wind, and in many cases the variability evident in the UV resonance line profiles of Be and (OB) stars may be attributed to changes in the strengths and/or velocities of the discrete absorption components (see e.g. Henrichs *et al.* 1983; Grady *et al.* 1987; Sonneborn *et al.* 1988; Doazan *et al.* 1989).

The total discrete component column densities (ΣN^D) of Be stars in our sample are typically ~ 14.5 dex cm^{-2} , which is comparable to the discrete component column densities observed in O stars (e.g. HP89). However, a larger number of individual features (typically two or three) contribute to the Be star sum (Section 5.1; Table 6). The ratio of the total observed C IV column density in discrete components to the column density in the 'underlying' P Cygni wind of Be stars [$= \Sigma N^D(\text{C}^{3+})/N^P(\text{C}^{3+})$; Tables 4 and 6] is plotted in Fig. 7 as a function of the projected rotation velocity. Typical values of $\Sigma N^D(\text{C}^{3+})/N^P(\text{C}^{3+})$ average ~ 40 per cent and may be ≥ 70 per cent, compared, for example, to the corresponding ratio of ~ 10 per cent

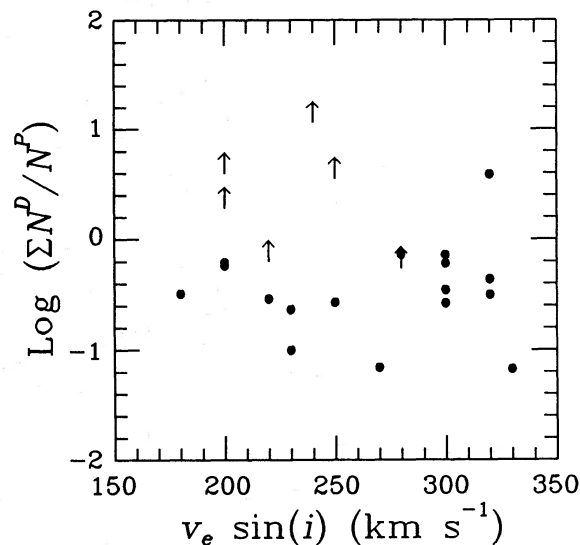


Figure 7. The ratio of total C^{3+} column density in discrete components (ΣN^D) to that in the 'underlying' wind (N^P) as a function of projected rotation velocity. Lower limit estimates are indicated for cases where only discrete absorption components are evident (see e.g. Fig. 4).

normally evident in O stars (HP89). The sum of the discrete component column densities relative to the strength of the ‘underlying’ wind is apparently not correlated with $v_e \sin(i)$.

The data in Fig. 7 emphasize that any discussion concerning the mass-loss properties of Be stars (derived from UV data) must acknowledge the (possibly substantial) contribution due to discrete components.

5.3.2 The product of mass-loss rate and ionization fraction ($\dot{M}\bar{q}_i$)

There are at least two principal problems in converting the stellar wind column densities quoted in Tables 4–6 into mass-loss rates:

(i) there is no straightforward method of incorporating the contributions due to discrete absorption component column densities into an expression for mass-loss rate without prior knowledge about the discrete component velocity distribution as a function of radial distance (which is unknown). We have demonstrated in Section 5.3.1 that their omission may *not* be a minor approximation.

(ii) the ionization fractions of ‘normal’ B and Be stars are very uncertain, and are not reliably predicted by current stellar wind model calculations.

We examine here, instead, the products of mass-loss rate and ionization fraction ($\dot{M}\bar{q}_i$), neglecting narrow absorption components, given by the relation

$$\dot{M}\bar{q}_i(w_1, 1) = \frac{4\pi m_E}{A_E} \frac{R_* v_* [N_i^P(0, 1) \{1 - w_1/z\}^{1+\gamma}]}{\int_{w_1}^1 \{\beta w^{(2\beta-1)/\beta}\}^{-1} dw} \quad (6)$$

(cf. HP89), where the ionization fraction $\bar{q}_i$ is averaged over $w_1 = 0.1$ to 1, A_E is the element abundance by mass fraction, and no allowance for discrete component absorption has been made. Note that, if $\mathcal{V}_*$ underestimates the ‘true’ terminal velocity of the outflow ($\mathcal{V}_\infty$) in weak winds (Section 4.1), then, as $\dot{M}\bar{q}_i \propto v_*^2$, the products of mass-loss rate and ion fractions quoted here would only be lower limits. Tables 7 and 8 give $\dot{M}\bar{q}_i$ data for Be and ‘normal’ B non-supergiant stars (respectively) in our sample for C iv, Si iv and Si iii. Errors in the stellar parameters, wind velocities and densities are unlikely to introduce errors in $\dot{M}\bar{q}_i$ exceeding a factor of 2. These data are plotted in Fig. 8 as a function of luminosity, together with corresponding O star data from HP89 (for unsaturated profiles only, i.e. mostly non-supergiant stars). The following principal points are noted from these figures for each ion.

C iv $\lambda\lambda 1548.2, 1550.8$ – The product $\dot{M}\bar{q}(\text{C}^{3+})$ is clearly a strong function of stellar luminosity in Be stars, as it is, for example, in O stars. The sparser Be star data set in Fig. 8 suggests a linear slope for this dependence of the form $\dot{M}\bar{q}(\text{C}^{3+}) \propto (L_*/L_\odot)^{0.95}$ which is a flatter dependence on luminosity than that quoted by HP89 for O stars [i.e. $\dot{M}\bar{q}(\text{C}^{3+}) \propto (L_*/L_\odot)^{1.59}$ – note that HP89 find the relation for O stars to be independent of luminosity class].

It is clear that the strengths of the ‘normal’ B star winds are not correlated with stellar luminosity (Fig. 8), and – with the exception of τ Sco (HD149438) – the products of $\dot{M}\bar{q}(\text{C}^{3+})$ in these stars are considerably lower than corresponding Be and O star values. We recall that, for the majority of ‘normal’ B stars in our sample, v_* does *not* exceed the photospheric escape velocity (Section 5.2.1), although the absence, for example, of redshifted absorption features may suggest that mass-loss is occurring.

Si iv $\lambda\lambda 1393.76, 1402.77$ – We have already alluded in Section 5.1.1 to the fact that the Si iv wind morphology in Be stars is exceptional compared to that of OB stars. The product $\dot{M}\bar{q}(\text{Si}^{3+})$ for Be stars is, once again, a strong function of stellar luminosity (Fig. 8). In contrast, HP89 found only a very weak dependence between the Si^{3+} wind density and luminosity in O giant and supergiant stars. The combined Be and O star data in Fig. 8(b) [which cover $\log(L_*/$

Table 7. The products of mass-loss rate and ionization fraction ($\dot{M}\bar{q}_i$) for Be stars.

HD	Log [$\dot{M}\bar{q}(C^{3+})$] ($M_{\odot} \text{ yr}^{-1}$)	Log [$\dot{M}\bar{q}(Si^{3+})$] ($M_{\odot} \text{ yr}^{-1}$)	Log [$\dot{M}\bar{q}(Si^{2+})$] ($M_{\odot} \text{ yr}^{-1}$)
5394	-10.46	...	...
58978	-10.37	-9.92	-10.50
180968	-9.97	-9.78	-9.88
110432	-9.95	-9.72	-10.40
212571	-10.64	-10.05	-10.57
63462	-10.19	-10.08	-11.36
28497	-10.51	-10.06	-10.25
35439	-10.55	-10.19	-10.47
200310	-10.61	-10.12	-10.46
52918	-10.45	-9.89	-10.43
44458	-10.94	-10.74	-10.62
68980	...	...	-11.00
148184	...	...	...
33328	-10.75	-10.56	-10.63
48917	-10.38	-9.91	-10.20
113120	-10.41	...	-11.43
50013	...	...	...
54309	...	...	-11.02
88661	...	...	-10.95
105435	...	...	-11.02
120324	...	...	-11.17
164284	...	...	...
30076	-10.77	-10.34	-10.51
208682	-11.10	-10.39	-10.57
157042	-11.04	-10.39	-10.75
56139	-11.88	...	-11.19
75311	...	...	-10.97
167128	-11.51	-10.98	-10.78
142983	...	...	...
217050	...	...	...
32991	...	-10.83	...
32343	...	...	...
58343	...	...	...
25940	...	...	...
91465	...	...	...
124367	...	...	...
22192	...	...	...
109387	...	...	...
112091	...	...	...
217891	...	...	...

$L_{\odot}$) ~ 3.5 to 6.0] are, however, consistent with the linear dependence on luminosity suggested by the Be data alone.

Much weaker Si^{3+} winds are noted for the non-emission B stars, with no dependence on luminosity (except that only the most luminous stars show any Si^{3+}).

Table 8. The products of mass-loss rate and ionization fraction ($\dot{M}\bar{q}_i$) for 'normal' B non-supergiant stars.

HD	Log [$\dot{M}\bar{q}(C^{3+})$] ($M_{\odot} yr^{-1}$)	Log [$\dot{M}\bar{q}(Si^{3+})$] ($M_{\odot} yr^{-1}$)	Log [$\dot{M}\bar{q}(Si^{2+})$] ($M_{\odot} yr^{-1}$)
149438	-10.02	-10.31	...
36512	-10.50	...	...
143275	-10.87	...	...
24760	-11.68	-11.06	...
111123	-11.13	-11.04	...
42933	-11.77	...	...
93030	...	...	...
118716	-11.87	-10.91	...
122451	-10.98	-10.96	...
37018	...	...	...
74575	-11.41	-10.98	...
129056	-11.05	-10.65	-11.00
160578	-11.79	-11.03	...
136298	...	...	...
151890	...	...	-11.45
127381	...	...	...
132058	...	...	...
3360	...	...	...
106490	...	...	-11.65
16582	...	...	-11.63
121743	...	...	...
132200	...	...	...
118079	...	...	...
148605	...	...	...
44402	...	...	...
125238	...	...	...
144294	...	...	...
193924	...	...	...
65575	...	...	...
74195	...	...	...
32630	...	...	...
41753	...	...	...
116087	...	...	...
45813	...	...	...
136664	...	...	...
22928	...	...	...
15371	...	...	...
98718	...	...	...
128345	...	...	...
106911	...	...	...

Si III λ 1206.51 – The products of $\dot{M}\bar{q}(Si^{2+})$ in Be stars (Fig. 8) are of the same order of magnitude as those noted for C^{3+} and Si^{3+} . A much weaker dependence on luminosity may be evident in these data, though the scatter is larger possibly as a result of the poorer data quality at these wavelengths and greater uncertainties in profile fitting. The limited corresponding

'normal' B star values are consistent with the suggestion of weaker winds in these stars relative to Be stars of the same spectral type and luminosity.

5.4 RELATIVE IONIZATION FRACTIONS

The $\dot{M}\bar{q}_i$ data in Tables 7 and 8, together with corresponding data from HP89, may be used to examine the mean (from $w=0$ to 1) relative ionization fractions, $\bar{q}_i/\bar{q}_j$, in the 'underlying' winds of Be, 'normal' B and O stars. Ratios of $\bar{q}(\text{C}^{3+})$, $\bar{q}(\text{Si}^{3+})$ and $\bar{q}(\text{Si}^{2+})$ are plotted, therefore, in Fig. 9 as a function of effective temperature, from which we note the following relations.

$\bar{q}(\text{Si}^{3+})/\bar{q}(\text{C}^{3+})$ – This ratio is clearly a decreasing function of effective temperature for Be, 'normal' B and O stars hotter than $\sim 24\,000$ K (Fig. 9). Comparable values of the ratio are noted for the three classes of stars at a given T_{eff} .

$\bar{q}(\text{Si}^{2+})/\bar{q}(\text{C}^{3+})$ – An inverse relation is apparent between the relative ionization fraction of Si^{2+} and C^{3+} for Be stars with respect to effective temperature (Fig. 9; unfortunately, no corresponding data are available for O and 'normal' B stars).

$[\bar{q}(\text{Si}^{2+}) + \bar{q}(\text{Si}^{3+})]/\bar{q}(\text{C}^{3+})$ – Only a very gradual decrease is apparent in this ratio as a function of effective temperature in Be stars (Fig. 9).

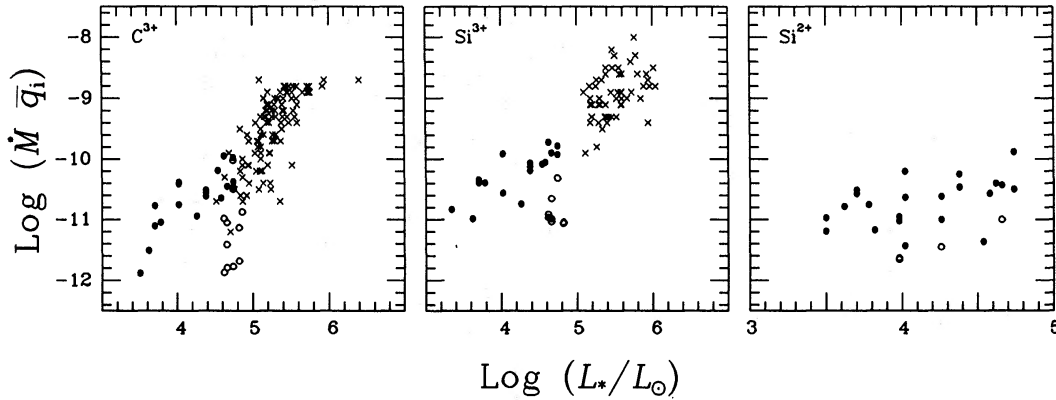


Figure 8. The product of mass-loss rate ($\dot{M}$) and ion fraction ($\bar{q}_i$) as a function of luminosity for C^{3+} , Si^{3+} and Si^{2+} . Filled circles correspond to Be stars, open circles are 'normal' B stars, crosses are the O star data from HP89.

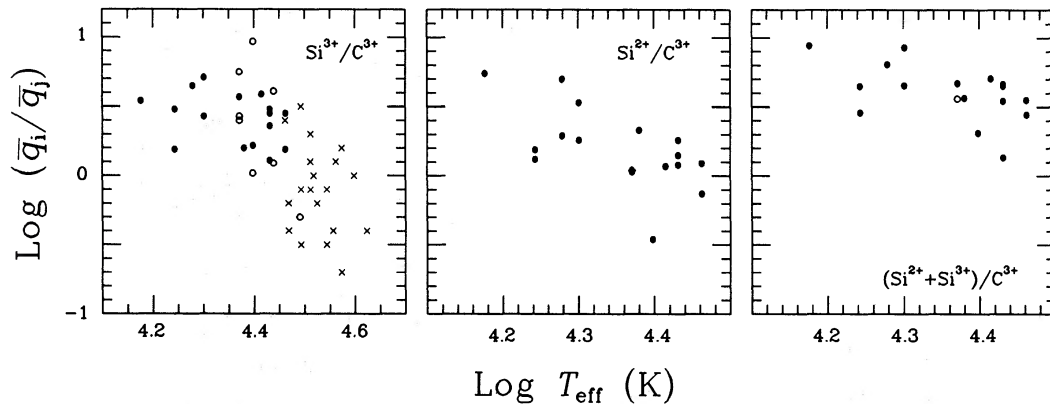


Figure 9. The relative ionization fractions ($\bar{q}_i/\bar{q}_j$) of $\text{Si}^{3+}/\text{C}^{3+}$, $\text{Si}^{2+}/\text{C}^{3+}$ and $(\text{Si}^{2+} + \text{Si}^{3+})/\text{C}^{3+}$ for Be ($\bullet$), 'normal' B ($\circ$) and O stars ($\times$; HP89).

6 Comparisons between UV, optical, IR and polarization observations

One of the intriguing aspects of Be stars is the wealth of their properties in many spectral regions, and it is clear that, ultimately, only detailed (contiguous) comparisons between observations at different wavelengths have the potential for distinguishing between rival models of the Be phenomenon.

In this section we compare the UV stellar wind properties derived here with published $H\alpha$ emission, IR excess and intrinsic polarization data (from different epochs) for our sample stars. Note that all these characteristics are potentially variable for a given star, and, for cases where no wind is evident in the UV spectra examined here (Table 4), strong $H\alpha$ emission, large IR excess and intrinsic polarization may, nevertheless, be noted from the literature.

6.1 BALMER EMISSION

Measurements of the $H\alpha$ emission strengths of Be stars were compiled from the surveys of Dachs *et al.* (1981), Andrillat & Fehrenbach (1982), Andrillat (1983) and Côté & Waters (1987). The $H\alpha$ equivalent widths may vary by ≥ 10 per cent over $\sim$ days to years; mean values were adopted and corrected for absorption due to the underlying stellar photosphere following the methods described by Côté & Waters (1987).

The estimated equivalent width of the $H\alpha$ emission line due to the circumstellar envelope of the Be star is plotted in Fig. 10(a) as a function of the product of mass-loss rate and C^{3+} ion fraction [$\dot{M}\bar{q}(C^{3+})$; Table 4]. These data do not suggest any simple relation between the strength of the $H\alpha$ emission and the (UV) stellar wind. The stellar wind velocities quoted in Table 4 (v_*) are much larger than those derived from the Balmer emission lines, which are typically ~ 100 – 500 km s $^{-1}$ wide (e.g. Dachs *et al.* 1981).

6.2 INFRARED EXCESS

Côté & Waters (1987) and Waters, Côté & Lamers (1987) describe in detail the IR characteristics of over 100 Be stars. Unfortunately, only a dozen of the stars they examined

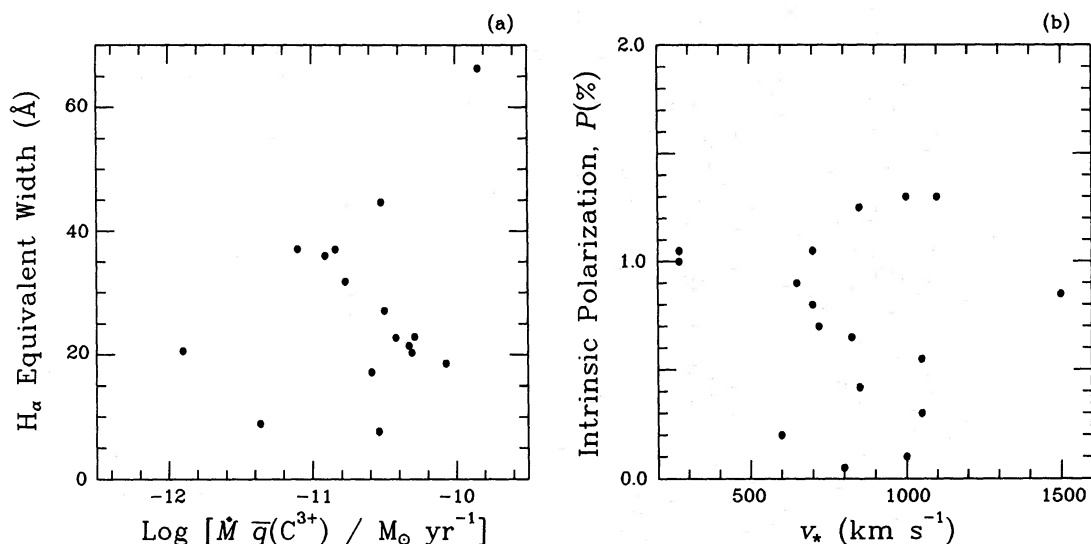


Figure 10. (a) The $H\alpha$ equivalent width (Section 6.1) versus the product of mass-loss rate and C^{3+} ion fraction for Be stars in our sample. (b) The intrinsic percentage linear polarization (from McLean & Brown 1978) as a function of the maximum observed wind velocity for Be stars.

also show observable evidence of a stellar wind in our UV sample. These limited data suggest no evidence, for example, for a relation between the colour-corrected 12 μm excess and the strength of the 'underlying' wind (for C IV, Si IV or Si III). The IR mass-loss rates of Waters, Coté & Lamers (1987) will be discussed further in Section 7.

6.3 INTRINSIC POLARIZATION

Observations of high degrees of polarization (most with constant polarization angles) in Be stars provide the strongest evidence for substantial departures from spherical symmetry in their circumstellar environment (e.g. McLean & Brown 1978). McLean & Brown (1978) present intrinsic circumstellar polarization measurements at $\lambda = 4250 \text{ \AA}$ for 67 high $v_e \sin(i)$ Be stars. The limited corresponding data in our UV sample which exhibit a stellar wind suggest no clear relation between intrinsic polarization, P (per cent), and the maximum observed wind velocity (v_* ; Fig. 10b). The strength of the wind or the relative contribution to the total wind column density due to discrete absorption components (e.g. $\Sigma N^D/N_p$; Section 5.3.1) are also unrelated to the degree of intrinsic polarization.

7 Discussion

7.1 UV MASS-LOSS RATES?

Waters, Coté & Lamers (1987) and Lamers & Waters (1987) have indicated that the mass-loss rates derived from *IRAS* IR observations of Be stars may be a factor of ~ 100 larger than those derived from UV data. These authors incorporate this apparent disparity, for example, into the *disc model* for Be stars (e.g. Struve 1931), where the UV lines are assumed to form in a high-velocity, low-density polar region, and the IR excess is associated with a high-density, low-velocity equatorial disc.

We have already cautioned in Section 5.3.1 about the difficulties of converting stellar wind column densities, obtained from UV line profile modelling, into mass-loss rates. For example, the mass-loss rates cited by Snow (1981) – which are used by Waters, Coté & Lamers (1987) for their comparisons – not only neglect discrete component contributions, but also assume an uncertain ionization balance, i.e. that all the silicon in the wind exists in the form of Si^{2+} and Si^{3+} . We recall from Section 5.4 that the relative ion ratio of $\bar{q}(\text{Si}^{2+})/\bar{q}(\text{Si}^{3+})$ in Be stars is related to the effective temperature.

Unfortunately there is currently no straightforward physical method to account for the contribution due to discrete absorption components. Intensive studies of wind variability in selected O stars (e.g. Prinja, Howarth & Henrichs 1987; Prinja & Howarth 1988) suggest that the discrete opacity enhancements may arise as a result of perturbations in the 'underlying' wind. These perturbations could, for example, be related to instabilities in the radiation-pressure-driven winds (Owocki, Castor & Rybicki 1988). It is clear that the physical nature of the progressive opacity enhancements is (unfortunately) complex; they may occur in winds which have non-monotonic velocity laws, they may not be spherically symmetric, and their migration in the absorption trough of a P Cygni profile may not represent the motion of a single mass-conserving feature.

We, therefore, only attempt here to estimate *lower limits* on the mass-loss rates of Be stars in our sample by considering just the contribution from the 'underlying' P Cygni profile (cf. Section 5.3.2). The lower limit estimates of $\dot{M}$ presented here are, however, still critically based on (alternative) *crude* estimates of the ionization balance in Be stars. They should be regarded as illustrations of the extent of uncertainty in UV mass-loss rates of Be stars.

7.1.1 Assuming $\bar{q}(\text{C}^{3+}) [\text{Be stars}] = \bar{q}(\text{C}^{3+}) [\text{O main-sequence stars}]$

The results of Section 5 suggest some similarities between the ambient winds of O-type and Be stars, and we highlight in particular the similar dependence of luminosity of the product $\dot{M}\bar{q}(\text{C}^{3+})$, and the comparable O and Be relative ionization fractions of $\bar{q}(\text{Si}^{3+})/\bar{q}(\text{C}^{3+})$ and $\bar{q}(\text{Si}^{2+})/\bar{q}(\text{Si}^{3+})$ at a given T_{eff} (Fig. 9).

In their survey of the winds of 203 O stars, HP89 derive a relation $\dot{M}\bar{q}(\text{C}^{3+}) \propto (L_*/L_\odot)^{1.59}$, which is consistent with the relation noted for the mass-loss rate ($\dot{M}$) from radio observations of luminous O stars. They derive, therefore, O star ionization fractions for C^{3+} (and N^{4+}) which are independent of effective temperature, but which increase by a factor ~ 2 , at fixed luminosity, going from main-sequence to supergiant stars. If we assume that the mass-loss rates of Be stars also follow this dependence on luminosity (Section 7.2) – and neglect (for the moment) any differences in slopes in Fig. 8 – then we may adopt for Be stars, the mean C^{3+} ionization fraction derived by HP89 for O main-sequence stars $= \bar{q}(\text{C}^{3+}) \sim -3.04$ dex (s.d. = 0.49). This value is independent of T_{eff} in the O star range of $\sim 49\,000$ – $32\,000$ K, and is extrapolated here for Be stars over $\sim 30\,000$ – $15\,000$ K (for *superionized* winds).

Adopting, therefore, $\bar{q}(\text{C}^{3+}) = -3.04$ dex in Table 4, gives Be star mass-loss rates in the range 1×10^{-7} – $2 \times 10^{-9} M_\odot \text{ yr}^{-1}$, which are compared in Fig. 11 (filled circles) with the corresponding IR values of Waters, Coté & Lamers (1987). These UV mass-loss rates are typically only a factor of ~ 3 lower than the corresponding IR values. It is acknowledged, however, that $\bar{q}(\text{C}^{3+})$ is unlikely to be the same for Be stars and O stars, and it is tempting to consider differences in the functional dependences of mass-loss rate and ion fractions with respect to the stellar luminosity.

7.1.2 Adopting $\dot{M}\bar{q}(\text{C}^{3+}) [\text{Be stars}] \propto (L_*/L_\odot)^{0.95}$

An alternative, therefore, is to suggest that the possible differences apparent in Fig. 8 for $\dot{M}\bar{q}(\text{C}^{3+})$ as a function of L_* between Be and O stars [$\propto (L_*/L_\odot)^{0.95}$ and $(L_*/L_\odot)^{1.59}$, respectively] are significant. In the absence of extensive ratio detections of Be stars, we still

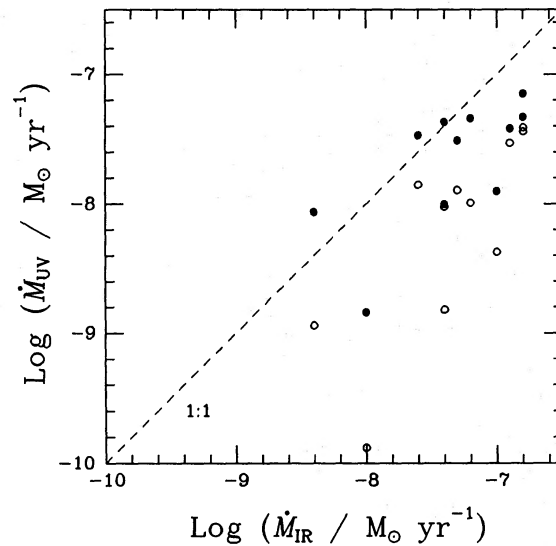


Figure 11. Comparison between the IR mass-loss rates of Be stars (from Waters *et al.* 1987) and corresponding UV values crudely estimated here by assuming (i) the mean O main-sequence star C^{3+} ion fraction quoted by HP89 (●), and (ii) that the difference in slopes of $\dot{M}\bar{q}(\text{C}^{3+})$ versus $\log(L_*/L_\odot)$ between O and Be stars in Fig. 9 is significant and is due to differences in the Be star ion fractions (open circles; see Section 7.1.2).

assume that the mass-loss rates of Be stars have the same dependence on luminosity as O stars [i.e. $\dot{M} \propto (L_*/L_\odot)^{1.69}$; which is reproduced by current radiation-pressure-driven wind theory predictions]. Therefore, we assume that the difference in these slopes is due to differences in the C^{3+} ionization fraction in Be stars relative to O stars. In this case, Fig. 8 suggests Be star ionization fractions which are typically a factor of ~ 5 – 10 times larger than those noted for O main-sequence stars. Estimates of Be star mass-loss rates based on 'scaled' O star C^{3+} ionization fractions are also plotted in Fig. 11 (open circles), where the data now suggest UV mass-loss rates which are on average a factor ~ 20 lower than corresponding IR values.

7.2 DRIVING FORCES IN BE STAR WINDS

7.2.1 Radiation pressure

The increasing ratio of v_*/v_{esc} as a function of effective temperature (Fig. 6a), the dependence of the product of mass-loss rate and ionization fraction on stellar luminosity (Fig. 8), and the occurrence of high wind velocities (Table 4), all highlight the similarities between the wind characteristics of Be- and O-type stars. These properties are in qualitative agreement with the predictions made by the radiation pressure-driven wind theory (which certainly dominates in O stars; e.g. Friend & Abbott 1986; Pauldrach, Puls & Kudritzki 1986).

Radiation pressure-driven wind models have been fairly successfully applied to Be stars, together with, for example, the effects of rapid rotation and/or magnetic fields (e.g. Marlborough & Zamir 1975, 1984; Poe & Friend 1986), and their role in these stars is increasingly recognized (see review by Marlborough 1987).

7.2.2 Additional mechanisms?

The Be and 'normal' non-supergiant B star results presented here (see also Barker, Landstreet & Marlborough 1984; Grady, Bjorkman & Snow 1987) suggest that there exists, for normal main-sequence stars, a fairly sharp division at spectral type B2, where only hotter stars show any evidence for a wind in their UV spectra. This division is in agreement with the radiation-pressure-driven wind theory prediction that the winds are self-initiating in stars more luminous than $M_{\text{BOL}} \sim -6$ (e.g. Abbott 1979, 1985). However, (superionized) winds are evident in the UV spectra of Be stars as late as B4 in our sample, and perhaps through the complete range of B spectral subtypes (e.g. Marlborough & Peters 1986; Grady, Bjorkman & Snow 1987). These observations raise the point that some additional mechanism may be relevant in cooler Be stars (e.g. $T_{\text{eff}} < 20\,000$ K) in order to provide the initial acceleration of the wind, which is subsequently driven to the terminal velocity by radiation pressure.

The role of rotation in enhancing the stellar winds has recently been reviewed by Marlborough (1987), and it is clear that the inclusion of both the finite angular-disc correction (e.g. Friend & Abbott 1986) and rotation (Poe & Friend 1986) in line-driven wind models predict slower, denser winds in the equatorial regions compared to the poles. These models are, therefore, consistent with suggestions that the optical and IR emission from Be stars originates in a cool disc-like equatorial region (e.g. Dachs *et al.* 1986; Lamers & Waters 1987). In addition, the suggestion in Section 5.2.2 of an increase in maximum observed wind velocities as a function of projected rotation velocity may relate to recent discussions concerning the role of magnetic fields in rapidly rotating stars (e.g. Poe & Friend 1986; Underhill 1987).

It is not true, of course, that rapid rotation alone can account for the observed differences between the winds of Be and comparable 'normal' non-supergiant B stars. We show in Fig. 12,

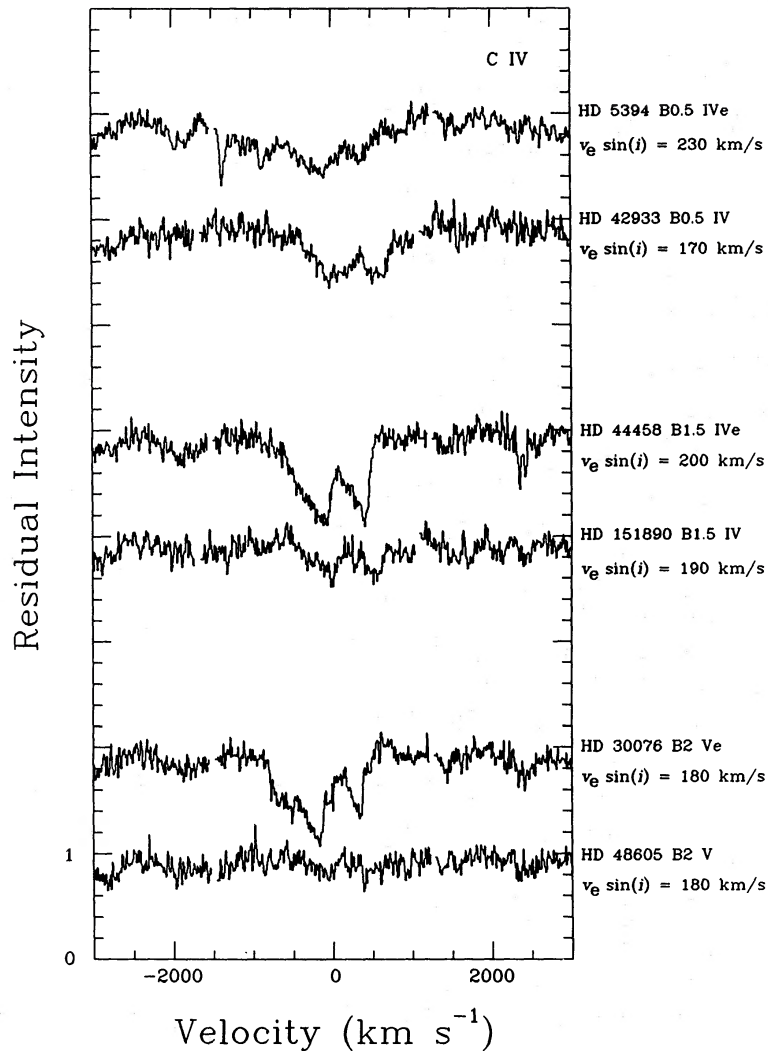


Figure 12. Examples of differences in the C IV profiles of Be and 'normal' B stars of identical B spectral type, and similar luminosities and projected rotation velocities.

for example, some cases of Be and 'normal' B stars of the same spectral type, and similar luminosities and projected rotation velocities; considerably stronger winds are still evident in the Be stars.

Baade (1987) has reviewed the recent realization that many Be stars exhibit photometric and spectroscopic (optical) line profile variations which may be interpreted in terms of travelling velocity fields at the photosphere and associated temperature variations; i.e. non-radial pulsations (NRP) of the photosphere. There is currently some speculation that NRPs may provide an additional driving mechanism for hot star winds (e.g. Vogt & Penrod 1983; Marlborough 1987). The occurrence of NRPs is, however, not restricted to just Be stars in the upper left-hand part of the HR diagram, but also extends to a wide range of early O and late B stars (Smith 1981; Baade 1987). Therefore, if NRPs have a major influence on the nature and appearance of Be star winds, then a physical difference between the pulsation properties of Be and 'normal' B stars may be expected (even when both are rapid rotators). There are suggestions that higher order or quadrupole modes which are most frequently observed in Be stars (e.g. Smith & Penrod 1984; Baade 1987) may, for example, provide tentative evidence for important differences in the NRP characteristics of these stars.

Clearly, a much larger database of *intensive* observations of selected Be and 'normal' B stars, covering UV winds, photospheric line profiles, H α profiles, infrared excess and polarization, are needed to address questions concerning wind driving mechanisms. Multi-wavelength studies of Be stars probably have the greatest potential for resolving between rival geometrical and physical models of the Be phenomenon.

7.3 THE UV PHOTOSPHERIC LINES

We cautioned in Section 3 that envelope and rotation effects may result in systemic differences between the fundamental parameters of Be and 'normal' non-supergiant B stars in our sample (e.g. Slettebak 1987). The exceptional Si IV $\lambda\lambda$ 1393.76, 1402.77 wind morphology as a function of luminosity class (Section 5.1) may already be an indicator of possible differences in the stellar parameters. The high-resolution *IUE* data of Be and 'normal' B stars examined here exhibit a large selection of photospheric lines whose properties may relate, for example, to the spectral types, effective temperatures and surface gravities of the stars. An analysis of silicon and carbon photospheric lines is briefly described below.

The observed equivalent widths of the C III λ 1247.38 photospheric lines are plotted in Fig. 13 as a function of effective temperature for the Be and 'normal' B stars in our sample. In both

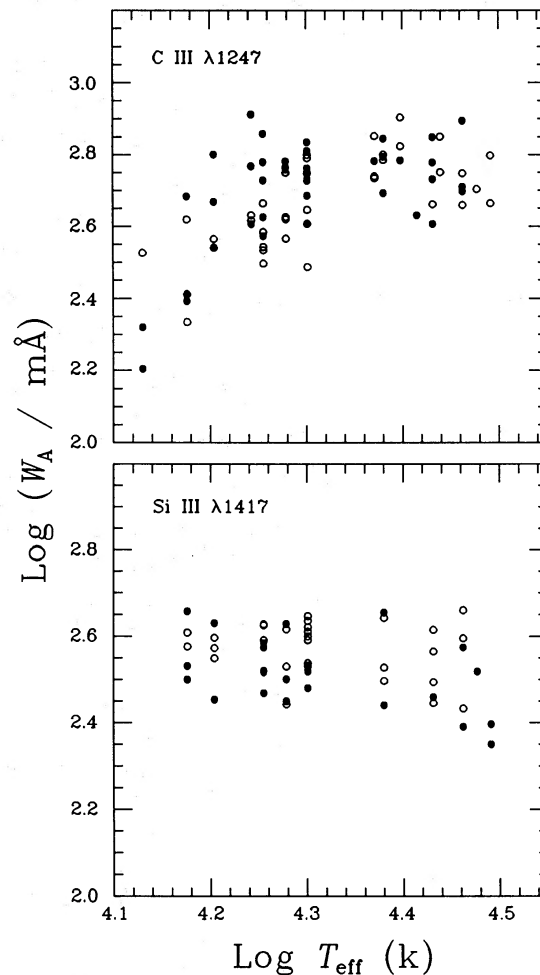


Figure 13. The equivalent widths of photospheric absorption lines due to C III and Si III as a function of effective temperature for Be (●) and 'normal' B (○) stars.

cases, there is some suggestion of a gradual increase in the strength of the C III line towards earlier spectral types. We do not find any significant differences between the observed equivalent widths in comparable Be and 'normal' B stars.

The Si III $\lambda 1417.47$ singlet is interesting because it is a sensitive function of the luminosity class; Massa (1988), for example, notes stronger Si III $\lambda 1417.47$ in B supergiants compared to main-sequence stars. The observed Si III equivalent widths for Be and 'normal' B stars are plotted in Fig. 13 as a function of T_{eff} , for main-sequence cases only (classes IV and V). The strengths are essentially independent of effective temperature and (again) no difference is evident between the Be and 'normal' B star datasets. (Note that the effect of rapid rotation will tend to reduce the equivalent widths as a result of lowering the apparent local continuum level.) No relative Si to C abundance variations are evident in our sample.

8 Conclusions

Results are presented from a study of the stellar winds of 40 Be and 40 non-emission 'normal' non-supergiant B stars, based on high-resolution *IUE* data. The observed C IV $\lambda\lambda 1548.2, 1550.8$, Si IV $\lambda\lambda 1393.76, 1402.77$ and Si III $\lambda 1206.51$ profiles are modelled using profile fits to determine the wind velocities and column densities. The relative contributions due to an 'underlying' P Cygni wind and multiple discrete absorption components are isolated. The characteristics of mass-loss in these stars are compared, together with those of O-type stars.

Some of the principal results of our study include:

- (i) Winds are evident in Be stars in our sample as late as B3 in C IV, Si IV and/or Si III, although some early-type Be stars may not show any observable evidence of mass-loss. Weaker, superionized, winds are also present in the most luminous 'normal' B stars.
- (ii) Discrete absorption components are observed in more than 50 per cent of the Be stars, and in some cases the total ionic column density due to discrete components may be ≥ 70 per cent of that due to the 'underlying' wind.
- (iii) Wind velocities of up to 1500 km s^{-1} may be noted in hottest Be stars. The ratio of v_*/v_{esc} for Be stars ranges from ~ 0.4 – 2.0 and is a strong function of effective temperature. No corresponding relation is noted for the 'normal' B stars, whose maximum observed wind velocities do not, in general, exceed the photospheric escape velocity. The Be star data suggest a trend of *increasing* v_*/v_{esc} as a function of $v_e \sin(i)/v_{\text{crit}}$.
- (iv) Typical Be star 'underlying' wind column densities range between ~ 13.8 – 15.5 dex cm^{-2} and are up to a factor of ~ 10 larger than corresponding 'normal' B star values. The product of mass-loss rate and ionization fraction ($\dot{M}q_i$) is a strong function of stellar luminosity for C^{3+} and Si^{2+} in Be stars. The linear slope of this dependence for C^{3+} may be shallower than that noted for O-type stars. Only the most luminous 'normal' B stars show observable evidence for a wind.
- (v) The relative ion fraction ratio of $q(\text{Si}^{3+})/q(\text{C}^{3+})$ is a decreasing function of effective temperature for Be, 'normal' B, and O stars hotter than $24\,000 \text{ K}$. Comparable values are noted between these stars at a given T_{eff} . The ratio $q(\text{Si}^{2+})/q(\text{C}^{3+})$ also decreases with rising T_{eff} in Be stars.
- (vi) Our limited data suggest no simple relation between the strength of the wind derived from UV data and the published $\text{H}\alpha$ emission strengths, IR excesses or intrinsic polarization of Be stars.
- (vii) Similarities between the properties of mass-loss in Be- and O-type stars point strongly to the active role of radiation pressure in providing the driving force for these winds. Additional physical mechanisms need to be invoked to provide the initial acceleration in cooler Be stars.

(viii) These data do not suggest any significant differences between the strengths of C III λ 1247 and Si III λ 1417 photospheric lines in the spectra of Be and 'normal' B stars.

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