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HIGHLY IONIZED STELLAR WINDS IN Be STARS: THE EVIDENCE FOR ASPECT DEPENDENCE

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ABSTRACT

We present the results of an ultraviolet survey of stellar winds in 62 Be and 43 normal B stars covering spectral types B0.5–B5 and luminosity classes V–III. We find that the wind absorption seen in the resonance lines of C IV, Si IV, and Si III in Be stars is often the result of blended absorption from multiple shortward-shifted discrete absorption components. We confirm the findings of earlier surveys, that shortward-shifted discrete components are not observed in normal nonsupergiant B stars, but are detected in 65% of our sample Be stars.

We find evidence of a threshold in $v \sin i$ for the presence of strong and highly variable winds in Be stars. Wind absorption in the form of shortward-shifted discrete components is observed only for Be stars having $v \sin i \geq 150$ km s^{-1}. Be stars with lower values of $v \sin i$ apparently do not exhibit high-velocity and strongly variable winds, and have C IV resonance line profiles indistinguishable from those seen in normal B stars. Comparison of the UV data with published infrared fluxes, continuum polarization data, and optical line profile atlases shows that these data sets also have similar thresholds in the vicinity of $v \sin i = 150$ km s^{-1}. The recent discovery that many, if not all, Be stars appear to be nonradial pulsators with characteristic pulsation modes, and the observation that the pulsation characteristics of these stars change at $v \sin i = 150$ km s^{-1} suggests that nonradial pulsation may be important in generating the Be phenomenon.

We present evidence that the high-velocity and highly ionized stellar wind observed in some, but not all, moderate to high $v \sin i$ Be stars is a function of latitude. Be stars showing shell spectra have distinctly different resonance profiles from those of other moderate to high $v \sin i$ Be stars, with little or no suggestion of high-velocity wind absorption. Instead the profiles are characterized by weak and apparently variable emission in C IV and single discrete components at -50 to -100 km s^{-1}. Two moderate $v \sin i$ Be stars in the sample have contemporary B band polarization measurements which have been separately reported. No correlation between optical-polarization episodes, which are presumably produced in a dense equatorial disk, and the characteristics of the highly ionized stellar wind has been observed. This lack of correlation suggests that the highly ionized portions of the stellar wind occur above the disk. The absence of strong and variable winds from low $v \sin i$ Be stars, which we believe are viewed at high latitude, is interpreted as evidence for the weakness of the wind at these latitudes. The resulting geometry for Be stellar winds and disk material corresponds to that expected for mass loss associated with nonradial stellar pulsations.

Subject headings: stars: Be — stars: early-type — stars: winds — ultraviolet: spectra

I. INTRODUCTION

Observations of emission-line B (Be) stars in multiple bandpasses have revealed that the atmospheres of these stars are extremely complicated and highly variable. High-velocity and highly ionized stellar winds from Be stars were detected in *Copernicus* spectra of a few bright Be stars (Marlborough and Snow 1980). *IUE* observations of Be stars have been more numerous and have covered a wider range in wavelength. Two complementary approaches have been used: (1) the surveying of a large number of stars with only a few observations for each; and (2) the regular monitoring of a smaller number of stars which show interesting characteristics. Previous surveys of *IUE* spectra have shown that superionization, or the detection of absorption from ionic species which are not expected to be present in the stellar atmosphere given the stellar $T_{\rm eff}$, is widespread in Be stars and appears to be less common among normal B stars (Marlborough and Peters 1982, 1986; Slettebak and Carpenter 1983). Shortward-shifted discrete components are frequently seen superposed upon the P Cygni resonance profiles of the more abundant ionic species in the O stars and B supergiants (Lamers, Gathier, and Snow 1982; Prinja and Howarth 1986). Henrichs (1984) in a survey of OB stars containing 30 Be stars found that for stars less luminous than $M_{\rm bol} = -7.5$ similar features occur only in Be stars, and that only 33% of the Be stars showed discrete absorption components. Barker and Marlborough (1985) in a survey of *IUE* data through 1983, found that only a few Be stars in their sample had variable wind profiles.

Monitoring of individual Be stars has also been highly productive. Studies of γ Cas (Henrichs *et al.* 1983), 59 Cyg (Doazan *et al.* 1985), ω Ori (Sonneborn *et al.* 1987), 66 Oph (Grady *et al.*

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1987*a*), and λ Eri (Barker 1986) have shown that in addition to wind profile variations on time scales of hours to months, several of these objects are variable on time scales of months to years. In these stars the longer term wind variability is in the form of episodes of enhanced-wind characteristics with intervening periods of months (66 Oph, 59 Cyg, λ Eri) to years (γ Cas) between the episodes. Between wind episodes, the resonance profiles of these stars are indistinguishable from those of normal B stars of comparable spectral type and luminosity class.

Additional *IUE* spectra of many Be stars are now available. The presence of additional spectra in the *IUE* archives, and the realization that, even for the stars with the most variable winds, long periods of quiescence occur, prompted us to make a more extensive survey of stellar wind properties among the early-type and middle-type Be stars in order to determine whether mass loss in these objects can be related to stellar parameters such as $T_{\rm eff}$, luminosity, and $v \sin i$.

II. PROGRAM STAR SELECTION CRITERIA

We have restricted our survey to B and Be stars with spectral types B0.5–B5 and luminosity classes V–III. Previous surveys of winds in Be stars have shown that highly ionized stellar winds are detectable in many Be stars as late as B5, and become much less common at B6 and later spectral types (Barker, Marlborough, and Landstreet 1984, hereafter BML). In addition, the frequency of the Be phenomenon peaks at B2 (Underhill and Doazan 1982). A further factor in the selection of this range in spectral type and luminosity is that the majority of the program stars are insufficiently luminous for radiation pressure alone to drive a strong and detectable stellar wind (Abbott 1982; Henrichs 1984). As a result of the recent interest in stellar winds from stars on or near the upper main sequence, a comparatively large number of bright Be stars in this range have been observed by the *IUE* in high dispersion. Many of these stars have been repeatedly observed as part of stellar wind programs, interstellar medium studies, and in studies of B star photospheres. In order to have *IUE* high-resolution spectra with moderate to high signal-to-noise, we have restricted our attention largely to bright B and Be stars with $V < 6.0$.

Since the available *IUE* data, and indeed the available catalogs of Be stars, do not form a complete or magnitude-limited sample, we have selected a sample of Be stars observed by *IUE*

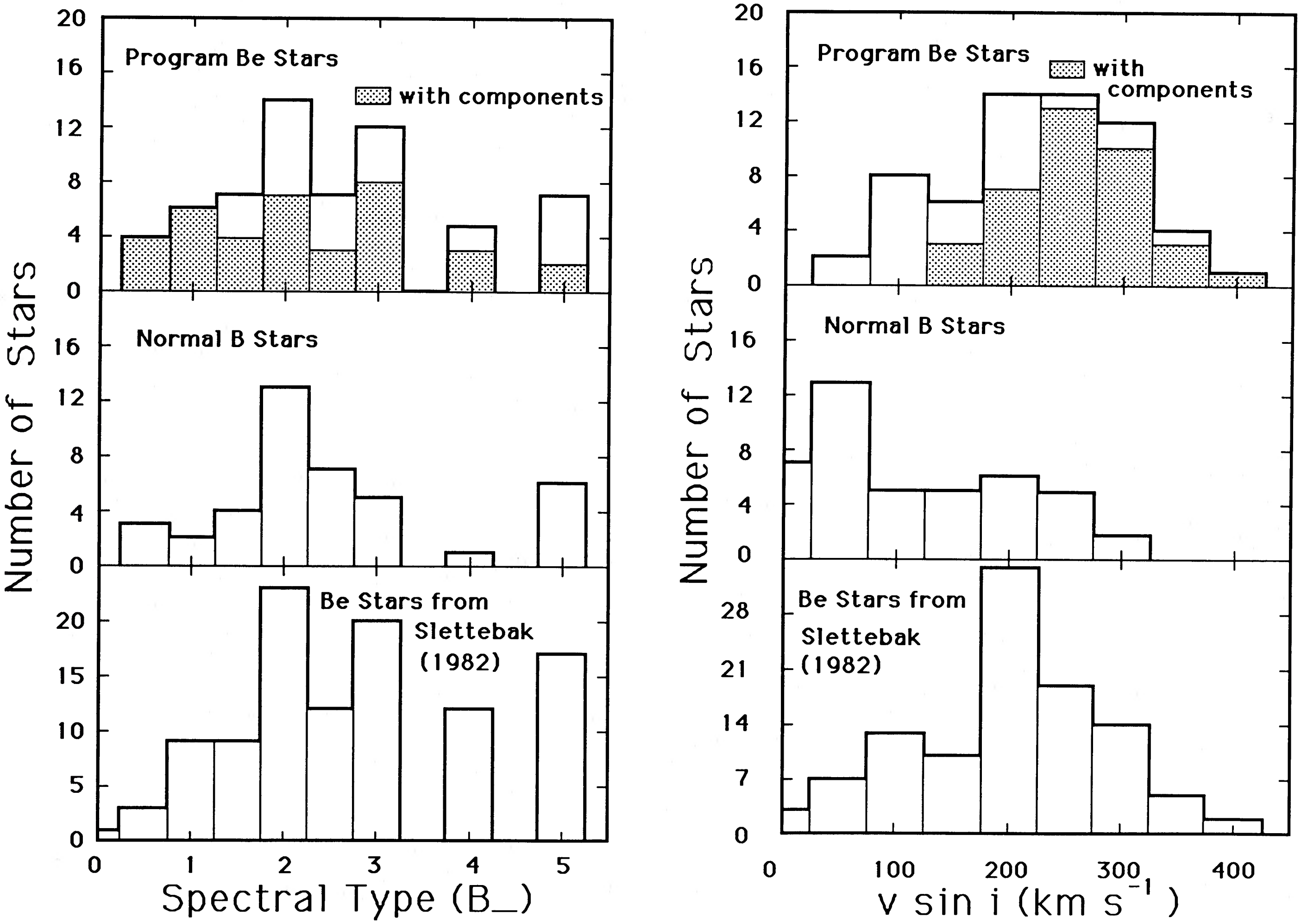

FIG. 1*a* FIG. 1*b*

FIG. 1.—(*a*) Distribution of B and Be stars in our sample as function of spectral type. Be stars showing discrete-component absorption indicated by shading. (*b*) Distribution of B and Be stars as function of $v \sin i$. Be stars showing discrete-component absorption indicated by shading. (*c*) Distribution of B and Be stars as function of luminosity class.

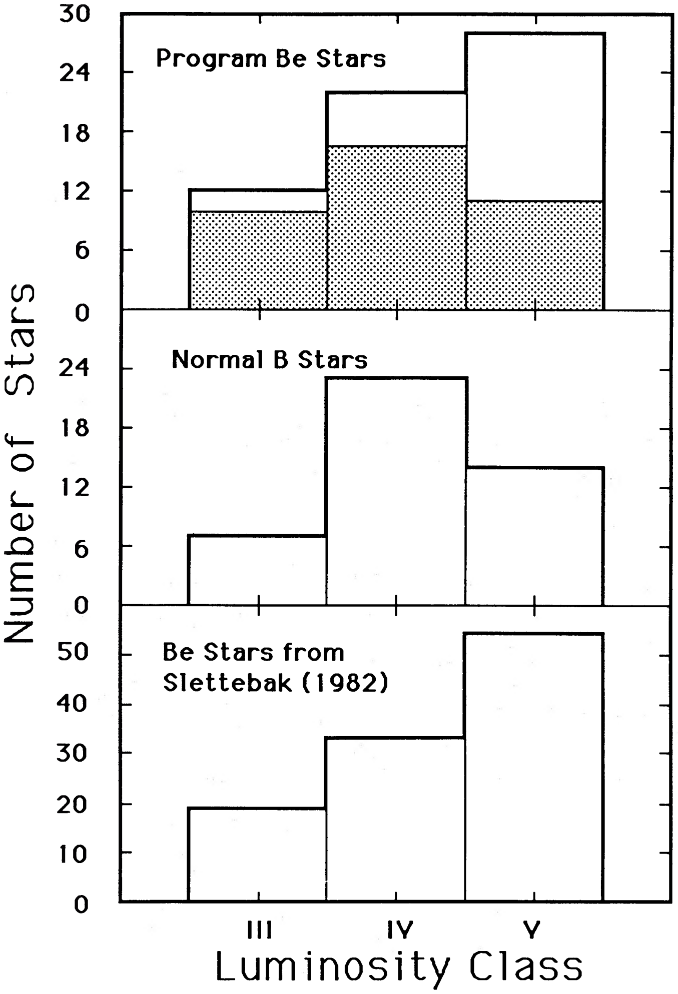

FIG. 1c

and matching the distribution of Be stars in Slettebak's (1982) catalog in spectral type and $v \sin i$ as closely as the available *IUE* data permitted. We have attempted to have several stars covering a range in $v \sin i$ at each spectral type and luminosity class. In some cases this has meant that we do not match the characteristics of Slettebak's sample precisely. Our sample contains proportionally as many low ($v \sin i < 150$ km s^{-1}) and high ($v \sin i > 350$ km s^{-1}) $v \sin i$ stars as does Slettebak's survey. Our sample contains 62 Be stars, 57 of which are cataloged by Slettebak (1982). The most recent large survey of Be stellar winds included single observations of C IV in 55 Be stars from B0–B5 (BML 1984) although later type Be stars were also considered. Figures 1*a*–1*c* show the distribution of our program Be stars with spectral type, $v \sin i$, and luminosity class, together with the properties of Slettebak's (1982) sample. We have also selected a group of normal B stars having *IUE* spectra. These comparison B stars have been selected to match the program Be stars in spectral type, luminosity class, and, to a lesser extent in $v \sin i$, and thus they may not be a representative sample of B stars. Table 1 lists the normal B star properties. Figures 1*a*–1*c* show the distribution of normal B stars in spectral type, luminosity class, and $v \sin i$. Table 2 lists the program Be stars.

III. OBSERVATIONS AND DATA REDUCTION

The *IUE* archives were searched for all short-wavelength (SWP), high-dispersion spectra of the program stars which were in the public domain by 1986 April 1. The archival spectra were supplemented by additional observations from other recent *IUE* observing programs with which we have been involved. A total of 511 Be star and 110 normal B star spectra were included in our survey. Of the most actively monitored Be stars, 10 account for more than 326 spectra. Fifteen of the Be stars and 25 of the B stars had single public domain spectra in the archives at our cutoff date. Of the Be stars 77% have multiple observations, as do 44% of the normal B stars.

The majority of the spectra were processed at the time of observation to the form of extracted spectra using the standard IUESIPS reduction software (see Turnrose, Harvel, and Stone 1981, or Turnrose and Thompson 1984). Observations obtained between 1978 June and 1979 July which originally were linearized incorrectly (Holm 1979) have been reprocessed. Correction for the echelle blaze function was made using the algorithm of Ake (1981). The *IUE* inverse-sensitivity calibration data of Cassatella, Ponz, and Selvelli (1981, 1983) were used to correct for wavelength-dependent variations in detector sensitivity. Data processed prior to 1981 November at Goddard Space Flight Center (GSFC) or 1982 March at the Villafranca Satellite Tracking Station (VILSPA) were smoothed using a three-point running-triangular filter. Spectra processed after those dates were smoothed using a five-point running-triangular filter. Reseau-contaminated portions of the spectra, typically no wider than 0.3 Å, were replaced by line segments linearly interpolated from the adjacent uncontaminated data. Overexposed data have been excluded from further analysis, as have data affected by telemetry dropouts. Obvious cosmic-ray hits resulting in spurious emission features have been removed from the line profiles. The data were checked for extraction errors following the procedure outlined in Sonneborn *et al.* (1987). Shortward of 1230 Å, extraction errors were found to be quite common, especially in earlier data, and were compensated for near 1200 Å by setting the fully saturated core of the Lyα profile to zero flux.

An archival program such as this one makes use of a large number of spectra originally obtained for very different purposes, resulting in a mixture of small- and large-aperture spectra, and in a range of exposure levels. Since the small-aperture observations are not suitable for absolute spectrophotometric measurements (Panek 1982), only relative measurements such as equivalent width measurements have been made. In optimally exposed early B star spectra, where a peak exposure level of 200–210 out of 255 data numbers (DN) is achieved in the vicinity of 1300–1400 Å, the smoothed data have signal-to-noise ratio S/N = 16–17. Less well-exposed spectra may have smoothed data S/N ratios as low as 10. The spectral smoothing slightly degrades the velocity resolution to ~30 km s^{-1} at 1550 Å. The early spectra, which were uncorrected for the spacecraft orbital velocity, may also have an uncertainty in the heliocentric wavelength scale as large as 25 km s^{-1}. The overall uncertainty in any radial velocity measurements is therefore ~50 km s^{-1}. Edge velocities (v_e) estimated from the radial velocity corresponding to the apparent return to continuum at the short-wavelength edge of the resonance profiles are estimated to be uncertain by at least 60–100 km s^{-1}.

Since published studies of the wind absorption from early Be

TABLE 1

NORMAL B STARS

No.	Name	HD	Type	$V \sin i$	V_e	Ion	$W_{\rm CIV}$	$W_{\rm SiIV}$	$W_{\rm SiIII}$	$W_{\rm NV}$	#	Comments
1	τ Sco	149438	B0 v	10	- 820	C IV	5.5	2.7	0.9	3.4	10	1
2	φ^1 Ori	36822	B0.5 IV-V	40	-1200	C IV	3.8	1.8	1.0	<2.3	1	2,3
3	δ Sco	143275	B0.3 IV	150	- 600	C IV	3.7	1.6	1.1	<1.0	5	1
4	β Cru	111123	B0.5 III	35	- 430	C IV	3.2	1.9	1.0	0.5	1	1 β Cep,2
5	ξ^1 CMa	46328	B1 III	10	- 340	Si IV	....	1.2	0.9	<2.1	8	3 β Cep,2
6	15 CMa	50707	B1 III	40	- 300	C IV	2.2	1.6	1.3	0.2	3	3 β Cep,2
7	1 Sco	141637	B1.5 Vn	300	- 450	Si IV	····	1.6	2.9	····	1	4, 5
8	λ Sco	158926	B1.5 IV	163	- 530	C IV	1.9	1.9	1.8	····	4	4,3 β Cep,2
9	μ^1 Sco	151890	B1.5 IV	235	- 450	C IV	1.5	2.2	1.7	3.3^b	3	1
10	δ Lup	136298	B1.5 IV	221	- 590	C IV	$<1.5^b$	2.2	2.7	····	3	1 β Cep,2
11	HR 1923	37356	B2 IV-V	10	- 220	Si IV	$<0.4^b$	1.3	1.9	····	1	6
12	10 Mon	45546	B2 V	79	- 520	Si IV	$<0.3^b$	1.3	3.5	····	1	6
13	β Mus	110879	B2 V	184	- 540	Si IV	····	1.3	4.8^b	····	2	1
14	δ Cet	16582	B2 IV	13	- 290	Si IV	<0.2	1.8	3.1	····	12	6 β Cep,2
15	ζ Cas	3360	B2 IV	18	- 410	C IV	2.9	2.1	3.8	1.4	10	1 β Cep,2
16	κ Cen	132200	B2 IV	10	- 390	Si IV	$<0.4^b$	1.5	4.0	····	3	1
17	θ Oph	157056	B2 IV	30	- 360	Si IV	$<1.1^b$	1.5	2.8	····	1	1 β Cep,2
18	6 Lac	213420	B2 IV	70	- 350	Si IV	$<1.0^b$	1.4	2.8	····	1	6,3
19	φ Cen	121743	B2 IV	80	......	Si IV	$<0.7^b$	1.3	3.8	····	1	1
20	ρ Sco	142669	B2 IV	155	- 390	Si IV	$<0.6^b$	1.3	3.7	····	1	4,3
21	δ Cru	106490	B2 IV	140	- 210	Si IV	0.8	1.4	2.7	····	1	1
22	σ Lup	127381	B2 III	60	- 480	C IV	1.7	1.6	2.1	····	2	1
23	β Lup	132058	B2 III	100	- 300	Si IV	$<0.9^b$	1.4	2.5	····	4	1
24	HR 3659	79351	B2.5 V	<40	- 140	Si IV	····	0.7	3.3	····	1	7
25	HR 5034	116072	B2.5 Vn	240	- 430	Si IV	0.7	1.4	1.9	····	1	4,3
26	θ Lup	144294	B2.5 Vn	270	- 300	Si IV	$<0.2^b$	0.9	3.3	····	1	1
27	114 Tau	35708	B2.5 IV	20	- 200	Si IV	$<0.5^b$	1.1	2.3	····	2	6,3
28	ζ CMa	44402	B2.5 IV	30	- 170	Si IV	<0.1	0.9	3.6^b	····	1	1
29	ζ Cen	121263	B2.5 IV	219	- 350	Si IV	$<0.3^b$	1.7	2.7	····	1	1
30	η Lup	143118	B2.5 IV	180	- 250	Si IV	$<0.5^b$	1.3	2.9	····	1	1
31	ψ Eri	32249	B3 V	80	- 240	Si IV	$<0.3^b$	1.0	3.6^b	....	1	5,3
32	χ Car	65575	B3 IV	50	- 210	Si IV	$<0.4^b$	0.7	3.9	....	1	1
33	σ Sgr	175191	B3 IV	205	- 390	Si IV	<0.3	1.6	3.2	....	5	4,3
34	ξ Ori	42560	B3 IV	220	- 450	Si IV	$<0.3^b$	0.9	3.2	....	3	6,3
35	53 Per	27396	B4 IV	15	- 210	Si IV	····	0.5	2.8	....	1	6,3,8
36	π And	3369	B5 V	35	- 50	Si IV	····	0.5	2.4	....	1	6,3
37	ψ^2 Lup	140008	B5 Vn	80	- 200	Si IV	0.1	0.4	2.9	....	1	4,5
38	π Lup	133242	B5 V	140	- 170	Si IV	....	0.5	1.8	....	1	4,3
39	β Cha	106911	B5 Vn	220	- 340	Si IV	$<0.4^b$	0.5	3.6	....	1	1,5
40	ψ^2 Aqr	219688	B5 Vn	280	- 390	Si IV	····	1.0	4.2	····	1	6,5
41	τ Her	147394	B5 IV	30	- 140	Si IV	····	0.5	4.0	····	3	1
42	2 Lac	212120	B6 V	40	- 100	Si IV	····	<0.5	^{b}	····	1	6,3
43	17 Tau	23302	B6 III	215	......	......	····	<0.4	3.6	····	3	5,3

NOTE.—In the sixth column, v_e is edge velocity for wind absorption. In the eighth through 11th columns, superscript indicates blended absorption, measurement uncertain or impossible. Numbers of SWP high-dispersion spectra included in survey are listed in the 12th column. In "Comments" column, β Cep indicates star identified as β Cep pulsating star. Other comments give references for spectral type and $v \sin i$ data. References are numbered as follows: (1) Slettebak *et al.* 1975; (2) Lesh 1982; (3) Uesugi and Fukuda 1982; (4) Hiltner, Garrison, and Schild 1969; (5) Hoffleit 1982; (6) Lesh 1968; (7) Slettebak 1982; (8) Smith 1977.

stars have shown that in many cases the observed profiles cannot be produced by any of the currently available models, we have made only empirical measurements of wind strength such as equivalent widths. The measured equivalent widths, which typically include all absorption in the resonance line profiles of N V $\lambda\lambda$1239, 1243, C IV $\lambda\lambda$1548, 1552, Si IV $\lambda\lambda$1394, 1403, and Si III λ1207, were measured using a straight line approximation to the local continuum of each individual spectrum and numerically integrating the absorption using the trapezoid rule. The equivalent widths are estimated to be uncertain by at least 0.05 times the maximum width of the feature (typically at the continuum) in optimally exposed spectra, and 0.1 times the feature width in less well-exposed data. Typical uncertainties for the earliest Be star equivalent widths are 0.35–0.5 Å, due to the extreme width of the profiles, and are as low as 0.1–0.3 Å for the later Be and normal B profiles. These uncertainties are caused by a combination of uncertainty in continuum placement, as a result of line blending in the vicinity of the resonance profiles, and by noise and other photometric errors in the *IUE* spectra.

Due to the large number of program star spectra in the *IUE* archives, we have attempted to reduce the necessary data analysis by identifying those stars with variable spectra. Variability in the resonance profiles was assessed for each of the ions of interest by visually inspecting plots of the profiles from each spectrum. When no significant changes in the profiles were

TABLE 2

Be STARS

No.	Name	HD	Spectral Type	$V \sin i$ (km s^{-1})	V_e	V_c	E/R	# Im.	Puls.
1	V1294 Aql	184279	B0.5 IVe[2]	250	-1430	- 80	S	2	
2	γ Cas	5394	B0.5 IVe[1]	230	-1600	-1360	E	40	
3	HR 2855	58978	B0.5 IVe[1]	280	-1200	0.,-200		16	
4	2 Vul	180968	B0.5 IVe[3]	330	-1300	- 920	S	11	Y
5	HR 1423	28497	B1 Ve[1]	230	- 940	- 140		4	
6	25 Ori	35439	B1 Ve[1]	320	- 920	- 150		11	
7	60 Cyg	200310	B1 Ve[1]	300	- 750	- 180		2	
8	59 Cyg	200120	B1 IVe[1]	260	-1000	- 800	R	73	Y
9	ο Pup	63462	B1 IVe[1]	320	-1570	- 450.,-370		2	
10	HR 4830	110432	B1 IIIe[4]	210	-2000	-1350	S	1	
11	π Aqr	212571	B 1 IIIe[1]	300	-1330	0.,-100		4	
12	31 Peg	212076	B1.5 Ve[1]	100	....	....		6	
13	χ Oph	148184	B1.5 Ve[1]	140	<-170	....		8	
14	HR 2284	44458	B1.5 IVe[1]	200	- 590	- 70.+more		2	
15	HR 3237	68980	B1.5 IVe[1]	115	- 800:	....		1	
16	19 Mon	52918	B1.5 IIIe[1]	270	-1100	- 860	S	4	Y
17	11 Cam	32343	B2 Ve[1]	100	....	....		3	
18	HR 7249	178175	B2 V(e)[1]	120	....	....		5	
19	56 Eri	30076	B2 Ve[1]	180	- 790	- 150.,500,670		10	
20	HR 3642	78764	B2 IVe[1]	120	- 600	0		3	
21	μ Cen	120324	B2 IV-Ve[1]	155	- 560	....		6	Y
22	κ CMa	50013	B2 IVe[1]	220	- 560	- 120		3	
23	HR 4009	88661	B2 IVe[1]	220	-1060	- 870		5	
24	δ Cen	105435	B2 IVe[1]	220	...[5]	....[5]	R	5	
25	66 Oph	164284	B2 IVe[1]	240	- 850	- 200	R	56	S
26	HR 2370	45995	B2 IVe[1]	250	- 490	- 100	S	2	
27	η Cen	127972	B2 IVe[1]	350	....	0	E	7	Y
28	HR 5223	120991	B2 IIIep[1]	70	- 290	0		1	
29	ω Ori	37490	B2 IIIe[1]	160	-1050	- 800	S	65	Y
30	λ Eri	33328	B2 IIIe[1]	220	-1050	- 860.,-940	R	20	Y
31	HR 7807	194335	B2 IIIe[1]	350	- 860	- 660		1	
32	ω CMa	56139	B2.5 Ve[1]	80	- 570:	....		5	
33	6 Cep	203467	B2.5 Ve[1]	150	- 800	- 500.,-300	E	19	
34	HR 3356	72067	B2.5 V(e)[1]	150	....	....		2	
35	ν Cyg	202904	B2.5 Ve[1]	180	- 550	....		1	
36	25 Cyg	189687	B2.5 V(e)[1]	200	- 520			1	Y
37	HR 3498	75311	B2.5 V(e)[1]	240	- 660	- 560		2	
38	HR 3186	67536	B2.5 Vn[3]	290	- 650	- 450	R	5	
39	HR 2825	58343	B3 Ve[1]	<40	...	...		6	
40	105 Tau	32991	B3 Ve[1]	200	- 600	- 550	S	3	
41	12 Vul	187811	B3 Ve[1]	230	...	...		6	
42	HR 7739	192685	B3 Ve[5]	250	- 930	- 670	R	9	
43	HR 2249	43544	B3 Ve[1]	300	...	...		1	
44	χ Car	65575	B3 IVp[1]	95	...	...		1	
45	HR 2921	60855	B3 IV[1]	230	- 610	- 50		1	
46	EW Lac	217050	B3: IV:e-s[1]	300	- 300	- 90		5	Y
47	28 Cyg	191610	B3 IVe[1]	320	- 600	- 200.,380	S	1	Y
48	48 Lib	142983	B3 IVe-sh[1]	400	- 350	- 80		11	
49	27 CMa	56014	B3 III(e)[1]	150:	-1200	- 0.,200		5	Y
50	ε Cap	205637	B3 IIIe[1]	350	- 640	-100		5	Y
51	48 Per	25940	B4 Ve[1]	200	...	...		3	
52	HR 4537	102776	B4 V(e)[1]	210	...	...		2	
53	α Eri	10144	B4 V(e)[1]	225	- 540	-190	E	3	Y
54	HR 5316	124367	B4 Ve[1]	300	- 550	- 290.,-110		1	
55	P Car	91465	B4 IVe[1]	250	- 540	- 200.,0		8	

TABLE 2—*Continued*

No.	Star Name	HD	Spectral Type	*Vsini* (km s^{-1})	V_e	V_c	E/R	# Im.	Puls.
56	β Psc	217891	B5 Ve^1	100	...	...		3	
57	μ^2 Cru	112091	B5 Ve^1	220	...	...		1	
58	HR 3858	83953	B5 Ve^1	260	...	...		2	
59	69 Ori	42545	B5 V^1	300	...	...		1	
60	o Cas	4180	B5 IVe^1	220	...	...		1	
61	κ Dra	109387	B5 IIIe^1	200	-500	-150	R	12	
62	ψ Per	22192	B5 IIIe^1	280	-515	-300		6	

NOTE.—In the fourth through sixth columns a colon indicates measurement uncertain. Superscripts following luminosity-class designations indicate sources of data. References for these data are as follows: (1) Slettebak 1982; (2) Ballereau and Chauville 1986; (3) Hoffleit 1982; (4) Jaschek and Egret 1982; (5) Barker and Marlborough 1985. In the eithth column, "E" indicates that a mass-loss episode has been observed with *IUE*, "R" indicates that recurrent episodes have been observed, and "S" indicates that mass-loss episodes are suspected. Number of SWP high-dispersion spectra surveyed for each star is given in the ninth column. In the 10th column, a "Y" indicates that line-profile variability typical of photospheric pulsation or photometric variability consistent with motion has been reported, and "S" indicates that pulsation is suspected.

detected, only one spectrum, typically the best exposed one, was measured for the star. When significant profile variation was seen, each profile was individually measured. Some of the stars included in this survey have previously published data; we have repeated the measurements done by other groups, but have directly quoted measurements done by one of us (primarily C. A. G.). The stars so affected include 59 Cyg (Doazan *et al.* 1985), ω Ori (Sonneborn *et al.* 1987), and 66 Oph (Grady *et al.* 1987*a*). We have tabulated the minimum and maximum observed C IV, Si IV, and Si III equivalent widths in Tables 1 and 3. No correction has been made for line blending in these data, or for the presence of photospheric absorption. An effort has been made to treat the stars similarly, although this is difficult when comparing spectra of rapidly rotating B stars having few resolved photospheric lines, and low $v \sin i$ objects, in which many more photospheric lines are resolved.

IV. RESULTS

a) Individual Stars

Figures 2*a* and 2*b* show C IV profiles for selected Be stars in our sample. Figures 3*a* and 3*b* show Si IV profiles for the same stars. Notes on the stars showing some line-profile variability are below. Equivalent widths for the normal B stars are contained in Table 1. Tables 2 and 3 give similar data for Be stars. Source information for spectral types and $v \sin i$ data are given in Tables 1 and 2.

i) *Nonemission B Stars with Variable Winds in our Sample*

ζ Cas (*HD 3360, B2 IV*).—The resonance profiles of this *IUE* high-dispersion calibration star show variable absorption both at the transition rest wavelength and at higher velocities. Smith (1977) reported that this star showed nonradial pulsation in its optical spectrum. C IV equivalent widths range between 1.9 and 3.2 Å. N V ranges between 0.5 and 1.4 Å. Si IV ranges between 1.2 and 2.0 Å. Si III and Al III are not detectably variable. Figure 4 shows the C IV profiles for this star.

σ Lup (*HD 127381, B2 III*).—The two *IUE* SWP spectra available show variable winds with profiles similar to ζ Cas. The C IV absorption ranges from 0.4 to 1.7 Å. Si IV and Si III are much less variable.

ii) *Be Stars with Components and Strong or Variable Winds*

γ Cas (*HD 5394, B0.5 IVe*).—Wind variability in this star has been extensively discussed by Henrichs *et al.* (1983). Recent Hα data are presented by Doazan *et al.* (1984). The wind absorption from this star is unusually weak for its spectral type. In addition to a strong P Cygni profile in the C IV and N V resonance lines, high-velocity discrete components have been observed in this star. Low-velocity discrete components have not been observed. This star is unusual among Be stars in being a hard X-ray source (Peters 1982*a*).

V1294 Aql (*HD 184279, B0.5 IVe*).—The UV spectra of this star shows evidence for strong shell absorption in the metastable Si II lines at 1533 and 1264 Å. The two *IUE* spectra included in our survey show that the wind profiles are significantly variable, and show the range typical of B0.5 IVe stars. Strong discrete component absorption is seen in the vicinity of -80 km s^{-1} in both spectra measured. Ballereau and Chauville (1987) have reported low-velocity enhanced absorption at -140 km s^{-1} in Hβ.

HR 2855 (*HD 58978, B0.5 IVe*).—The resonance profiles of C IV, Si IV, N V, and Si III in this star are characterized by multiple discrete components originally noted by Peters (1982*c*). Strong multiple components are present in all 16 *IUE* SWP spectra. The low-velocity components are strongest. One component, present in all spectra, is located at the transition rest wavelength. Si III and N V are especially variable in this star, and appear to be anticorrelated. Significant emission is present in N V, and to a lesser extent in C IV. Dachs *et al.* (1986) report extremely broad Hα profiles with extended emission wings and asymmetric absorption lines from 1980–1983. Pastori (1987) reports radial velocity variations in this star which may suggest that it is a binary. Representative C IV and Si IV profiles for this star are shown in Figures 2*b* and 3*b*.

HR 7318 (*2 Vul, HD 180968, B0.5 IVe*).—The available *IUE* spectra of this star show strong moderate- and high-velocity absorption. The weakest spectrum obtained to date (SWP 15214) shows partially resolved discrete component absorption, while the remaining spectra show "trough" absorption of the form described by Barker and Marlborough (1985). The identification of this star as a Be star is due to Barker (1983), who obtained Hα profiles over the same time interval as that

TABLE 3

Equivalent Widths for the Be Stars

No.	C IV		Si IV		Si III		N V		SWP	images
	min	max	min	max	min	max	min	max	min	max
1	3.1	5.2	2.1	2.7	1.6	3.1	:	:	17840	6034
2	2.9	3.9	1.2	2.1	0.2	0.2	0.6	0.9	14873	8724
3	4.6	5.9	2.8	3.5	1.1	2.4	1.8	2.3	15053	15957
4	4.7	6.0	3.2	3.6	1.8	3.0	0.6	1.7	15214	18364
5	3.6	4.0	2.9	3.2	2.2	3.4	0.5	1.5:	4051	18944
6	4.0	4.0	3.1	3.2	2.5	3.1	0.2	0.2	21910	27493
7	3.5	4.2	2.7	2.9	2.3	2.5	2.3	2.4	10853	19939
8	0.5	5.0	2.8	2.8	2.8	2.8	0.0	2.2	16695	7891
9	5.9	5.9	2.5	2.6	1.0	1.1	2.5	3.0	21951	20838
10	5.0	···	3.4	···	···	···	2.1	···	13759	
11	4.7	5.2	3.8	4.3	2.5	3.7	1.4	2.3	2784	5886
12	<0.5	···	2.0	···	3.0	···	···	···	15934	
13	0.45	···	1.8	···	1.8	···	···	···	5956	
14	3.2	···	2.6	···	3.0	···	···	···	16550	
15	1.0	···	1.9	···	2.7	···	···	···	22119	
16	2.9	4.4	2.8	3.7	2.5	3.1	1.5	1.7	22113	21913
17	<0.2	···	0.6	···	2.0	···	···	···	6932	
18	1.2	···	1.4	···	2.2	···	···	···	15058	19928
19	3.3	3.9	2.2	2.3	3.5	4.0	···	···	20844	27474
20	1.5	···	1.4	···	3.1	···	···	···	20357	
21	0.5	···	1.3	···	3.2	···	···	···	15962	
22	0.6	···	2.0	···	2.2	···	···	···	15029	
23	1.0	1.2	1.5	1.7	2.2	2.6	···	···	14434	14908
24	<0.3	···	1.9	···	2.7	···	···	···	15961	
25	0.5	3.1	1.4	2.6	2.3	3.9	···	···	25653	17975
26	0.9	1.1	2.3	2.3	3.3	3.5	···	···	16550	9936
27	1.9	3.1	2.4	3.0	3.0	3.3	···	···	19613	18858
28	1.5	1.7	2.5	3.0	2.5	2.6	···	···	7751	27458
29	3.0	5.1	1.9	3.2	3.5	3.8	···	···	18185	15982
30	1.6	3.0	1.9	3.3	1.9	2.7	···	···	27425	21493
31	1.9	···	2.0	···	2.8	···	···	···	19938	
32	1.0	···	1.1	···	3.8	···	···	···	15028	
33	0.5	2.9	1.3	1.9	2.8	4.2	···	···	5908	27428
34	1.2	···	1.4	···	3.0	···	···	···	5492	
35	0.5	···	1.1	···	3.4	···	···	···	8601	
36	1.2	···	1.5	···	3.6	···	···	···	19936	
37	<0.3		0.5	1.4	2.9		···	···	22118	22098
38	0.7	1.6	1.4	1.8	2.6	2.8	···	···	2747	20356
39	<0.2	···	0.4	···	3.3	···	···	···	21914	
40	···	1.9	···	1.8	···	3.0	···	···	·····	21490
41	···	···	···	···	···	···	···	···	20849	
42	0.7	2.8	1.0	1.9	3.3	3.5	···	···	20439	26843
43	<0.1	···	0.9	···	···	···	···	···	21911	
44	<0.1	···	0.7	···	3.2*	···	···	···	20355	
45	3.0	···	2.1	···	2.7	···	···	···	21915	
46	0.9	···	0.7	···	2.1	···	···	···	19323	
47	1.7	···	1.8	···	3.0	···	···	···	8600	
48	1.1	···	1.1	···	1.8	3.3	···	···	16678	
49	2.5	3.0	2.0	2.3	2.0	2.4	1.5	1.8	14481	3392
50	1.0	1.4	1.4	1.7	2.7	3.1	···	···	21164	19615
51	<0.1	···	0.6	···	*	*	···	···	24051	
52	0.2	···	0.7	···	3.3	···	···	···	···	22095
53	1.0	1.4	1.0	1.3	2.6	3.6	···	···	21156	5887
54	1.0	···	0.7	···	3.0	···	···	···	26126	
55	1.1	2.1	1.4	2.0	2.7	3.5	···	···	21161	21689
56	<0.2	···	:	···	*	*	···	···	15935	
57	···	···	···	···	*	*	···	···	21955	
58	···	···	···	···	*	*	···	···	22120	
59	<0.3	···	<0.4	···	*	*	···	···	9896	
60	···	···	···	···	*	*	···	···	20436	
61	···	0.8	0.6	0.9	···	···	···	···	4475	20985
62	0.6	1.3	0.9	1.2	2.0	3.8	···	···	29270	15513

NOTE.—Asterisk indicates that Si III absorption is severely blended with Lyα absorption. A colon indicates measurement uncertain. The SWP high-dispersion observation numbers corresponding to minimum and maximum wind-strength spectra are listed in the 10th and 11th columns.

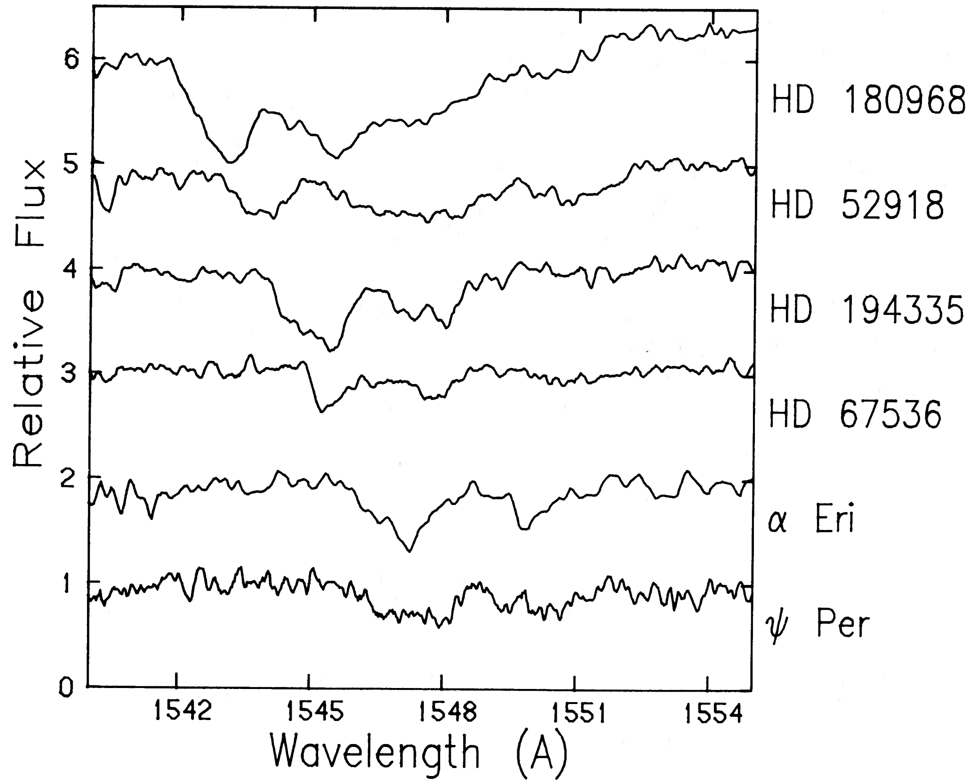

FIG. 2*a*

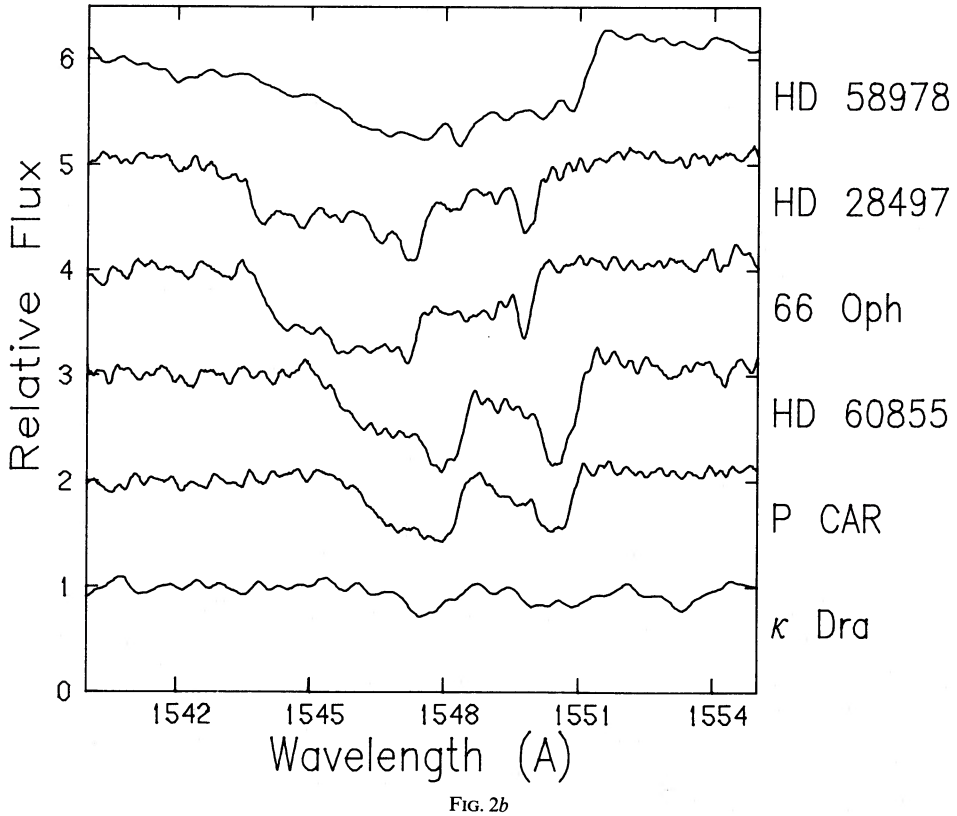

FIG. 2*b*

FIG. 2.—Selected C IV line profiles. (*a*) Spectra showing strong high-velocity components for B0.5e–B5e. Actual velocity of components declines as function of spectral type. (*b*) Spectra showing low-velocity components. Some of these stars also show high-velocity components, but lowest velocity component is typically strongest.

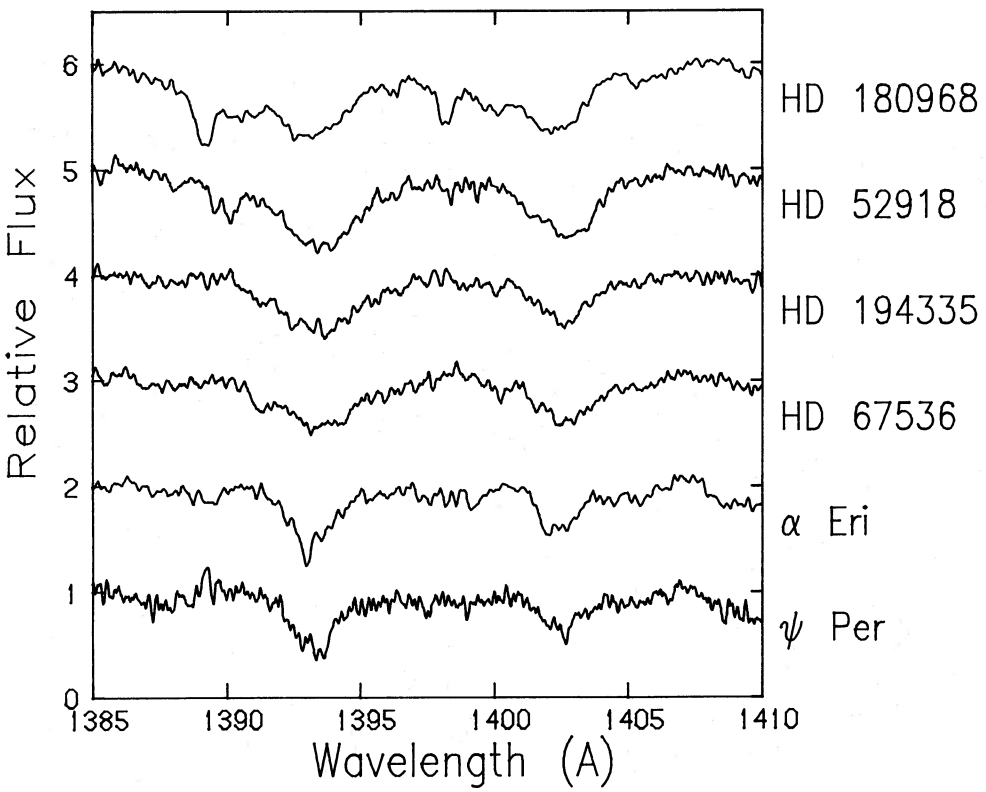

FIG. 3*a*

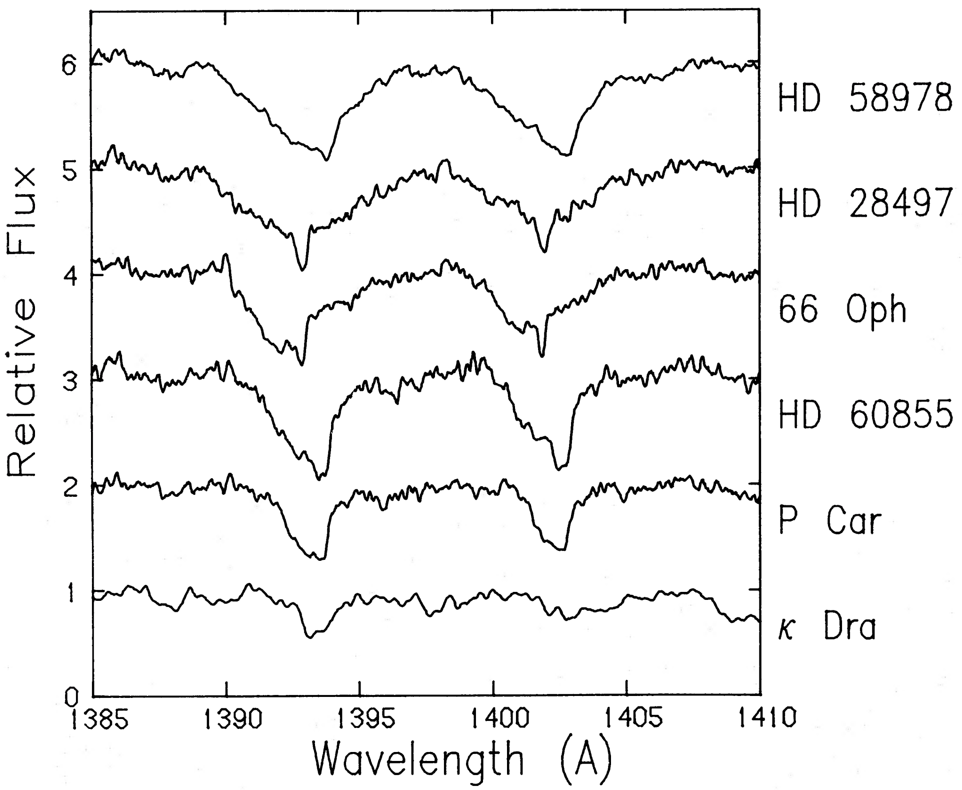

FIG. 3*b*

FIG. 3.—Selected Si IV line profiles for same stars and images as in Fig. 2. (*a*) Spectra showing strong high-velocity components in at least one spectrum. (*b*) Spectra showing strong low-velocity or unshifted components.

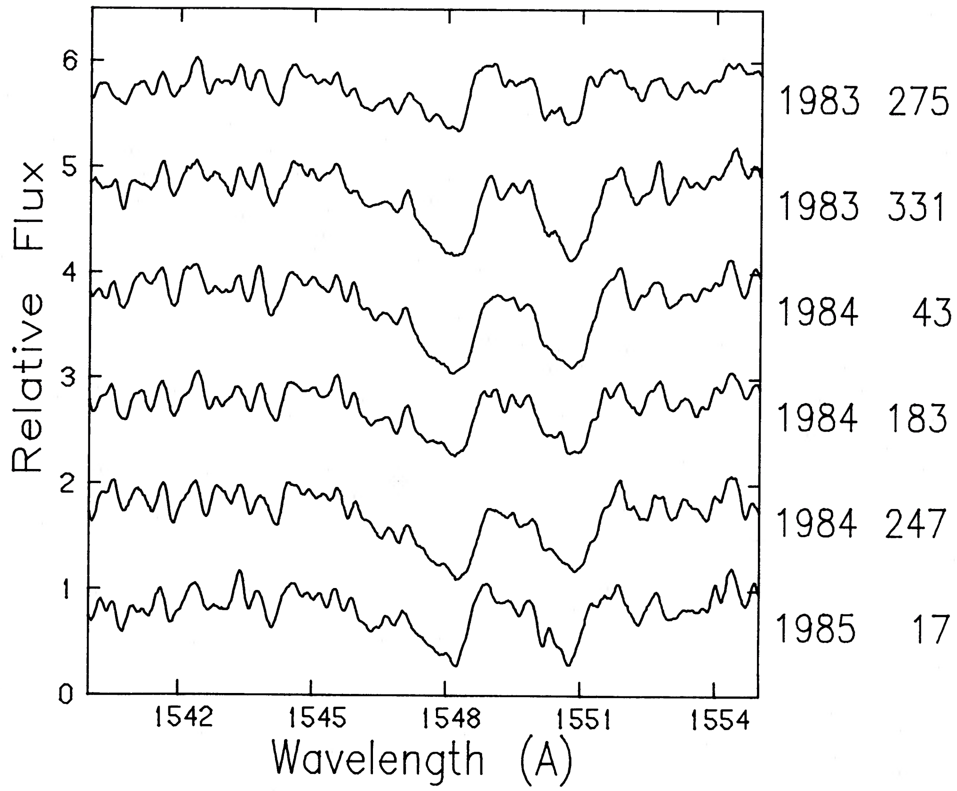

FIG. 4.—C IV in ζ Cas as function of time. Time of observation specified as year and day of year.

over which the majority of the *IUE* data were obtained. Percy (1985) reports that this star shows the short time scale photometric variations which have been interpreted as evidence for nonradial pulsation. Representative C IV and Si IV profiles for this star are shown in Figures 2*a* and 3*a*.

HR 1423 (*HD 28497, B1 Ve*).—Wind absorption is detected in C IV, Si IV, Si III, Al III, and possibly N V. The resonance profiles are characterized by a strong low-velocity discrete component. Dachs *et al.* (1986) present asymmetric Hα and double Hβ emission profiles between 1980 and 1983. Representative C IV and Si IV profiles for this star are shown in Figures 2*b* and 3*b*.

25 Ori (*HD 35439, B1 Ve*).—Wind absorption in this B1 Ve star is seen in C IV, Si IV, Si III. Little N V is detected. Barker (1983) presents Hα data for this star.

60 Cyg (*HD 200310, B1 Ve*).—This star shows strong low-velocity discrete absorption components in both of its *IUE* SWP spectra. Strong absorption is seen in Si IV and Si III. Barker (1984) summarizes the Hα data for this star.

o Pup (*HD 63462, B1 IVe*).—This star shows strong N V, C IV, Si IV, and only a trace of absorption in Si III. The strongest discrete component is in the vicinity of -350 to -450 km s^{-1}. Dachs *et al.* (1986) report only small variations in Hα equivalent widths, but V/R variations in the profile.

HR 4830 (*HD 110432 B1 IIIe*).—Prinja and Henrichs (1987) summarize the currently available *IUE* spectra of this star. The only SWP image in the public domain at the cutoff date of our survey showed unusually high velocity absorption in C IV, with a strong high-velocity discrete component in C IV and Si IV, and no detection of Si III. Prinja and Henrichs (1987) obtained additional *IUE* spectra in 1986 March and found much stronger wind absorption.

π Aqr (*HD 212571, B1 IIIe*).—This bright Be star known for its optical shell spectra has been relatively infrequently observed by *IUE*. Strong low-velocity absorption components characterize its resonance profiles on N V, C IV, and Si III.

HR 2284 (*HD 44458, B1.5 Ve*).—Both *IUE* SWP spectra of this star show strong low-velocity absorption in C IV, Si IV, and Si III. Unusually strong Al III and S III λ1202 absorption is also present.

59 Cyg (*HD 200120, B1.5 IVe*).—C IV and Hα variations in this star from 1978 to 1983 have been discussed by Doazan *et al.* (1985). The *IUE* data show variable N V and C IV, with high-velocity absorption most frequently seen in the C IV profiles. This star has undergone repeated strong-wind episodes, which are apparently correlated with the Hα V/R ratio. *IUE* spectra obtained in mid-1986 show that especially strong wind absorption is not confined to the early stages of a Be phase, as had been thought previously.

19 Mon (*HD 52918, B1.5 IIIe*).—The profile variations seen in the four *IUE* SWP spectra of this star are reminiscent of those in 59 Cyg. Strong high- and low-velocity discrete components are observed. The maximum wind velocity in this star ranges from -1100 km s^{-1} down to -730 km s^{-1}. This star has been noted as a β Cep star. Representative C IV and Si IV profiles are shown in Figures 2*a* and 3*a*.

56 Eri (*HD 30076, B2 Ve*).—This star has strong low-velocity discrete absorption components in C IV, and strong absorption in Si IV and Si III. Small-amplitude changes in the C IV profile were detected during 1986 January (Grady *et al.* 1987*b*). Dachs *et al.* (1986) present Hα–γ data from 1980–1983.

HR 3642 (*HD 78764, B2 IVe*).—The *IUE* spectra of this star show intermediate-strength C IV absorption with the strongest absorption at the transition rest wavelength, reminiscent of some of the β Cep stars. This object should be reobserved to determine whether the wind is variable. Persi and Ferrari-Toniolo (1987) note that the infrared spectrum of this Be star is unusual in showing a strong dust excess.

κ CMa (*HD 50013, B2 IVe*).—This star shows weak and variable C IV absorption in the two *IUE* spectra inspected, similar to that observed in 66 Oph close to minimum wind strength. This star should be reobserved to determine whether its stellar wind goes through episodes similar to those seen in 66 Oph. Dachs *et al.* (1986) obtained optical observations of this star from 1978–1983. Double structure is visible in Hβ from 1981–1983 when Hα showed only broad, single emission profiles.

HR 4009 (*HD 88661, B2 IVe*).—Variable C IV and Si IV with resolved high-velocity discrete-component absorption characterizes the *IUE* spectra of this star. Dachs *et al.* (1981) reported strong Hα emission with variable equivalent widths. A large drop in the equivalent widths was seen in early 1982 (Dachs *et al.* 1986). This object is a suspected hard X-ray source (Peters 1982*a*).

δ Cen (*HD 105435, B2 IVe*).—This star showed no detectable wind absorption in the spectra included in our survey. However, *Copernicus* observations show clear wind absorption (Snow, Oegerle, and Polidan 1980), and Henrichs (1986*b*) reports strong C IV absorption in an *IUE* spectrum obtained in 1986 March. Dachs *et al.* (1986) present optical data for this star.

66 Oph (*HD 164284, B2 IVe*).—*IUE* data from 1979 to 1982 February are presented in Barker and Marlborough (1985). Additional data from 1982 April through 1985 June are presented in Grady *et al.* (1987*a*). This star has episodically variable wind absorption in which the profile strength and appearance are related. The strong-wind episodes are of variable duration. Recent *Voyger* observations of this star (Peters and Polidan 1987) show that the far-ultraviolet flux from 66 Oph is variable, and the high-flux state may correspond with wind minimum, and the weak-flux state with wind maximum. Representative C IV and Si IV profiles are shown in Figures 2*b* and 3*b*.

HR 2370 (*HD 45995, B2 IVe*).—Low-velocity discrete-component absorption is present in the two *IUE* SWP spectra of this star.

η Cen (*HD 127972, B2 IVe*).—This star has been repeatedly observed by *IUE*, and has shown only unshifted absorption. The resonance profile of C IV is similar to that of C IV in some β Cep stars and includes enhanced, unshifted absorption. The C IV, Si IV, and Si III equivalent widths are not variable, although significant profile shape changes are observed. Dachs *et al.* (1986) report variable shell absorption in the Balmer lines of hydrogen.

HR 5223 (*HD 120991, B2 IIIep*).—The ultraviolet spectrum of this object resembles those seen in the classical shell stars such as 48 Lib. Some absorption is seen in the vicinity of the C IV resonance transitions, and is tentatively identified as C IV, although this identification is highly uncertain.

ω ORi (*HD 37490, B2 IIIe*).—The ultraviolet wind variation in this star is discussed by Sonneborn *et al.* (1987), who find no correlation between the presence of linear polarization episodes and wind characteristics. The wind from this star has been especially strong in over 6 yr of *IUE* monitoring. No weak-wind episodes have been detected. Baade (1986) observed line profile variations characteristic of nonradial pulsation in 1985 January. Optical polarization episodes have been reported by Hayes (1980), Guinan and Hayes (1984), and Hayes and Guinan (1984). Dachs *et al.* (1986) present additional optical spectra.

λ Eri (*HD 33328, B2 IIIe*).—Ultraviolet wind variations in this star were initally reported by Barker and Marlborough (1985). Subsequent work has suggested that the wind episodes are correlated with changing nonradial pulsation behavior and with Hα episodes (Barker 1986, Penrod 1986). This result should be accepted with some caution since the ultraviolet and optical data were not obtained simultaneously. The wind from this star is considerably weaker than that detected in ω Ori. Observations made in 1985 October and 1986 January through 1986 March showed that the star showed essentially normal B-star absorption levels in the C IV, Si IV, and Si III resonance profiles. Smith *et al.* (1987) report the presence of transient features in optical photospheric line profiles which may be associated with extremely short-lived Hα emission episodes. *IUE* spectra obtained at nearly the same time showed only weak C IV and Si IV absorption (Grady *et al.* 1987*b*).

HR 7807: (*HD 194335, B2 IIIe*).—The single *IUE* spectrum of this star shows strong high-velocity discrete components in C IV. The C IV and Si IV profiles are shown in Figures 2*a* and 3*a*.

6 Cep (*HD 203467, B2.5 Ve*).—Barker and Marlborough (1985) initially reported the presence of discrete-component absorption in this star, as well as the detection of a weak-wind episode. The strongest discrete component in this object is typically at high velocity.

HR 3498 (*HD 75311, B2.5 Ve*).—This object shows extremely weak C IV absorption with discrete components. Dachs *et al.* (1986) report a Balmer absorption spectrum in late 1981, which changed over to double emission profiles with V/R ratios of approximately unity by early 1983. The *IUE* spectra included in our study come from 1983.

HR 3186 (*HD 67536, B2.5 Vn*).—Strong C IV, Si IV, and Si III absorption with a well-developed high-velocity discrete component characterize the wind absorption from this star. Overall, the profiles are reminiscent of 6 Cep. C IV and Si IV profiles are shown in Figures 2*a* and 3*a*.

105 Tau (*HD 32991, B3 Ve*).—This star shows strong C IV with high-velocity discrete components and has been discussed by Barker and Marlborough (1985). Hα data is presented by Barker (1983).

HR 7739 (*HD 192685, B3 Ve*).—Strong wind absorption in this star was initially reported by Barker and Marlborough (1985). A high-velocity discrete component is strongly present in C IV, Si IV, Si III, and Al III. Barker (1983) presents Hα profile data.

HR 2921 (*HD 60855, B3 IVe*).—As shown in Figure 2*b*, this star's C IV profile is characterized by a strong low-velocity discrete component and weaker high-velocity absorption. Si IV is similar. C IV and Si IV profiles are shown in Figures 2*b* and 3*b*.

EW Lac (*HD 217050, B3 IV: e-sh*).—In common with 48 Lib, no high-velocity wind absorption is seen in this object, despite several observations made with the *IUE*. C IV absorption at low velocity is present. There is a suggestion of weak emission in C IV. The identification as C IV is somewhat uncertain since the spectrum of EW Lac is heavily contaminated by strong Fe absorption.

28 Cyg (*HD 191610, B3 IVe*).—Multiple discrete absorption components characterize the wind from this star. The resonance profiles are strikingly similar to those seen in 66 Oph during wind maximum. This star is also known to be a nonradial pulsator (Percy 1985).

48 Lib (*HD 142983, B3 IVe-sh*).—Wind absorption from this object was discussed in Slettebak and Carpenter (1983). Variable C IV emission is present. No high-velocity wind absorption is detected, in common with other Be stars in our sample having shell spectra. Dachs *et al.* (1986) report that the Hα emission equivalent width in this star has remained relatively constant since 1950. Balmer absorption line cores were present throughout most of the hydrogen Balmer series. Strong shell absorption in Fe II, Ti II, and Si II was present in 1982.

27 CMa (*HD 56014, B3 III(e)*).—This object has an extremely strong and high-velocity wind for its spectral type. Strong zero-velocity discrete components are seen in the five *IUE* spectra. N V is present at zero velocity in this object and varies in antiphase with Si II. N V and C IV emission are present.

ϵ Cap (*HD 205637, B3 IIIe*).—This object shows variable continuum fluxes throughout the *IUE* spectral region. Polidan and Carone (1986) have detected emission in C IV in an *IUE* spectrum obtained during 1986 April. Earlier *IUE* spectra did not suggest the presence of emission. The strongest discrete-component absorption in this star, which may well be a binary, is located at zero velocity. Dachs *et al.* (1986) report a slight decrease in Hα equivalent widths and emission intensity from 1978 to 1981. From 1981 to 1982 they report constant equivalent widths, but variable V/R ratios.

α Eri (*HD 10144, B4 V(e)*).—This star, which is a nonradial pulsator (Percy 1985), shows strong low-velocity discrete-component absorption in at least one of its three *IUE* spectra. One spectrum corresponds to nondetection of the wind. Dachs *et al.* (1986) report a decrease in Hα and Hβ emission strength since 1978. C IV and Si IV profiles are shown in Figures 2*a* and 3*a*.

HR 5316 (*HD 124367, B4 Ve*).—This star shows multiple low-velocity discrete-component absorption. Dachs *et al.* (1986) report a decrease in Hα emission strength from 1978 to 1983. At their resolution Hα–Hβ show single absorption profiles, whereas Hγ is double.

P Car (*HD 91465, B4 IVe*).—The available *IUE* spectra of this star show blended absorption features in the resonance profiles of C IV, Si IV, and Si III. The strongest absorption is at very low velocity. Overall, the profiles resemble those in ϵ Cap. No continuum variability is seen, although comparison of SWP 21161 and SWP 21689 suggests that variable C IV emission is present. Dachs *et al.* (1986) present an extensive discussion of the optical spectrum of this star. Hα equivalent widths remained approximately constant from 1980 to 1983, although considerable changes in profile shape were observed. C IV and Si IV profiles are shown in Figures 2*b* and 3*b*.

κ Dra (*HD 109387, B5 IIIe*).—Weak but variable discrete-component absorption in C IV is seen in the majority of the 12 available *IUE* SWP spectra of this object. C IV and Si IV profiles are shown in Figures 2*b* and 3*b*.

ψ Per (*HD 22192, B5 IIIe*).—*IUE* spectra of this star were presented in Slettebak and Carpenter (1983). Variable absorption is present in C IV. Mg II shows faint double emission. C IV and Si IV profiles are shown in Figures 2*a* and 3*a*. Additional *IUE* spectra obtained during 1986 show that the C IV absorption faded in 40 days from 1986 August 8 to 1986 September 21.

b) *Wind Strength and Superionization*

Previous studies of winds in B and Be stars have shown that at least some Be stars have both stronger wind absorption than normal stars and show superionization compared to normal B stars (Snow 1981, 1982; Marlborough and Peters 1982, 1986; BML 1984). Measurement of wind strength and the detection of superionization are tied together since the resonance lines which are the most sensitive probes of the stellar wind are also the indicators for superionization. Previous studies have either been restricted in the number of lines and the range of ionization potential covered (Snow 1981, 1982; BML 1984), or have considered only a limited number of stars and few spectra from each star (BML 1984; Marlborough and Peters 1986). As noted by BML (1984), some Be stars show C IV absorption as late as B9, whereas the normal stars do not have detectable C IV absorption later than B2. We find similar results with C IV present throughout our Be star sample, but not detected in the B stars later than B2. N V is detected in our Be stars as late as B3, and is undetected in the *IUE* spectra later than B1–B2 in the normal B stars. As noted by Slettebak and Carpenter (1983), Si IV is unexpected in B stars later than B3. We find Si IV absorption in the Be stars in our sample as late as B5, and only sometimes present for the normal B stars at B4 and B5. Our results for Si III are less conclusive since this line is sensitive to blending from nearby spectral lines of other species, and at the later spectral types in our sample, Lyα.

Previous surveys (Marlborough and Peters 1982, 1986; BML 1984) have shown that a distinguishing characteristic of the ultraviolet spectra of some Be stars is the strength of absorption in C IV, Si IV, and occasionally N V compared to that observed in normal B stars. Figure 5*a* (*upper*) shows the maximum C IV absorption detected for each Be star as a function of spectral type. Figure 5*a* (*middle*) shows the same data for the comparison B stars. Figure 5*a* (*lower*) shows the excess C IV absorption for the Be stars over that of the normal B stars with a mean normal B-star C IV absorption subtracted. Even allowing a generous uncertainty in the C IV equivalent widths from B0 to B2 of 0.7 Å, and assuming that this uncertainty is equivalent to 1 σ for the normal star distributions, it is clear that some Be stars have excess C IV absorption which is 3–6 σ above that seen in the majority of the normal B stars. From B3 to B5, where C IV absorption is not detected in the normal B stars, Be excesses of 1–2.5 Å are observed, and are significant at the 1–3 σ level. Figure 5*b* shows the Si IV for Be stars and the comparison normal stars, as well as the excess Si IV in the Be stars with average normal B star equivalent width subtracted. Similar, although less significant conclusions can be drawn from the Si IV data.

Inspection of these figures shows that the strength of C IV and Si IV exceeds that observed in normal B stars for many, but not for all of the Be stars in our sample. Some of the stars in our sample (59 Cyg, 66 Oph, ω Ori) have been the subjects of long-term monitoring programs. The observed C IV and Si IV absorption in these stars can range from equivalent widths indistinguishable from those measured in normal B stars to values comparable to those expected in late O stars. For example, Doazan *et al.* (1985) found the C IV equivalent width in 59 Cyg to vary between 1.1 and 5.4 Å. The range of C IV equivalent widths is shown for 10 of the stars with the most complete monitoring data in Figure 6. Even where the equivalent widths do not change significantly, the profile shapes are observed to be variable.

c) *Discrete Components*

The most striking feature of the resonance profiles of C IV in many Be stars is the presence of shortward-shifted discrete

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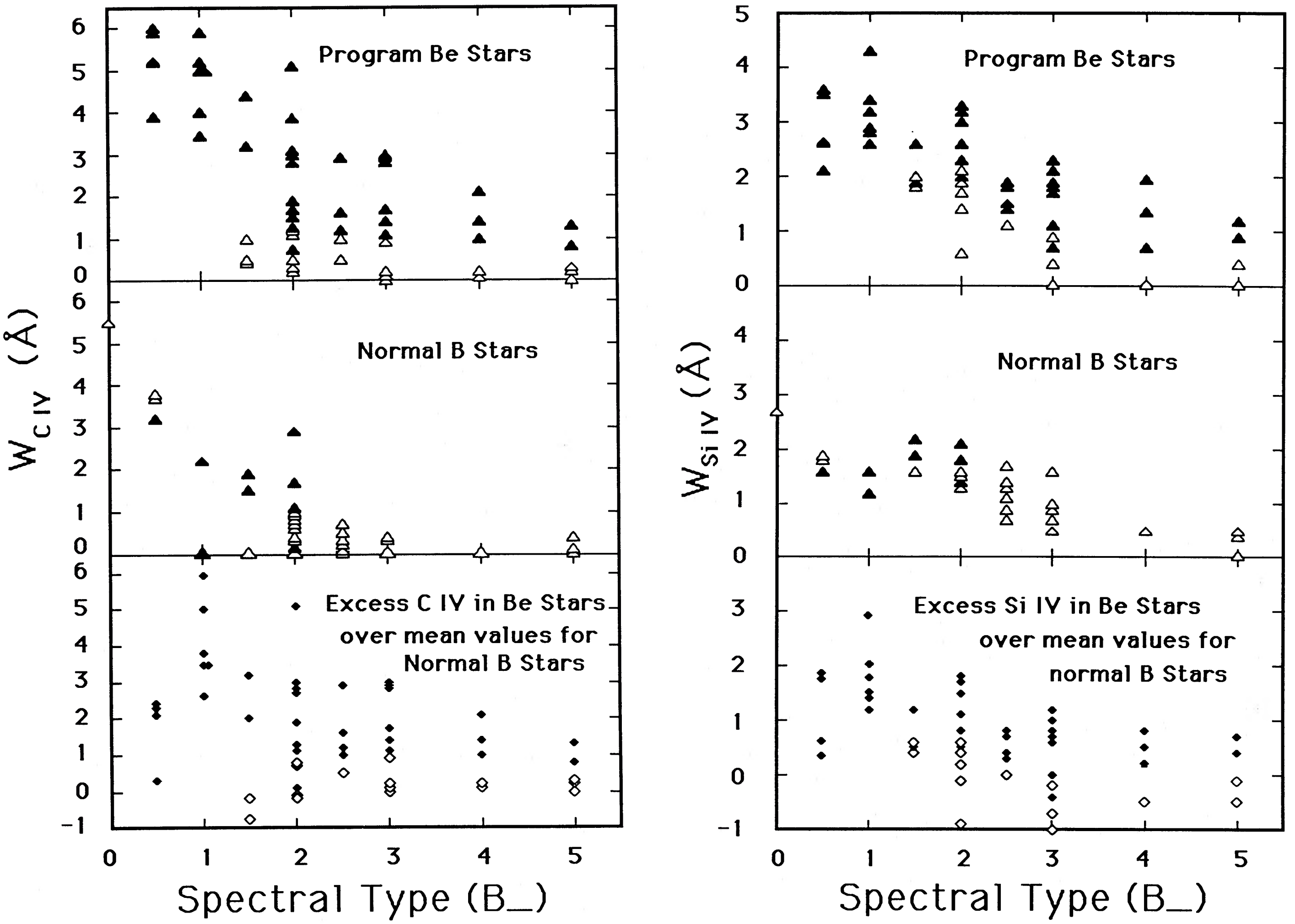

FIG. 5*a*

FIG. 5*b*

FIG. 5.—Wind strength and superionization in B and Be stars. (*a*) C IV in Be (*upper*) and B (*middle*) stars. C IV excess over normal shown for Be stars in lower panel. Stars with discrete-component absorption indicated by filled symbols. (*b*) Si IV in Be (*upper*) and B (*middle*) stars. Si IV excess over normal shown for Be stars in lower panel.

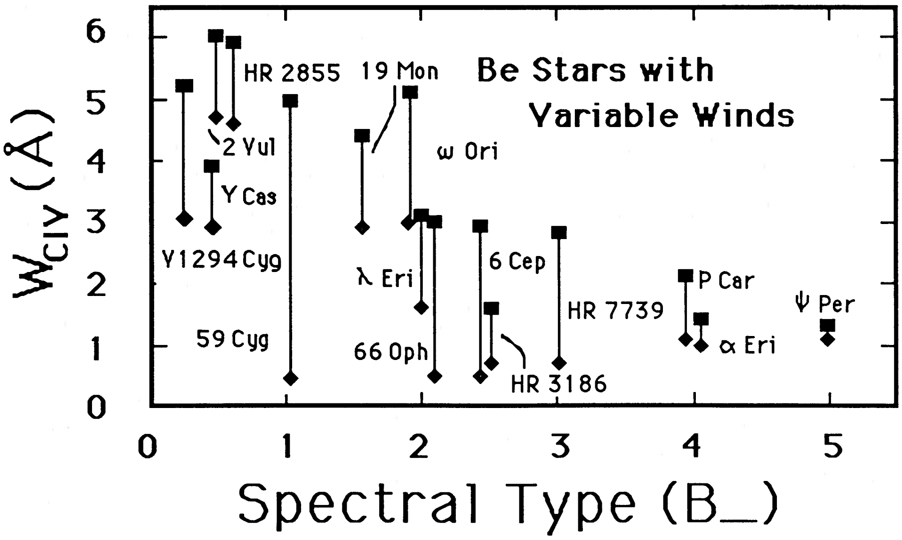

FIG. 6.—Variation in C IV equivalent widths for selected Be stars

absorption components. Forty (65%) of the Be stars in our sample have been observed to have at least one discrete absorption component in at least one *IUE* spectrum. Previous studies limited to fewer stars and fewer spectra of each star found that only 50% of the Be stars showed discrete absorption features (Henrichs and Wakkers 1986). The distribution of stars showing component absorption as a function of spectral type, $v \sin i$, and luminosity class is shown in Figures 1*a*–1*c*, Figure 2*a* shows that, for our sample, the stars having discrete absorption features form the majority of Be stars showing C IV absorption significantly above normal B-star levels. This result, coupled with similar conclusions drawn from the line profile variation studies of individual Be stars (see Grady *et al.* 1987*a*; Sonneborn *et al.* 1987), suggests that much, if not all, of the excess wind absorption is in the form of discrete components.

Shortward-shifted discrete components are also observed in the UV resonance profiles of O stars (Lamers, Gathier, and Snow 1982; Prinja and Howarth 1986). In the case of the O stars, the discrete components, while observed at least some fraction of the time in all of the stars surveyed by Prinja and Howarth (1986), can be treated as a perturbation on a well-defined P Cygni profile which is not detectably variable. In the case of the Be stars, the observed discrete components do not form a small perturbation on an essentially quiescent P Cygni profile. In the majority of the Be stars in our sample, the component absorption dominates the resonance profiles of C IV, and, to a lesser extent, those of Si IV, and Si III. From B2 to B5, C IV is not detected in normal B stars, and essentially all of the wind absorption in the Be stars comes from the discrete components.

Studies of discrete absorption components in O stars (Lamers, Gathier, and Snow 1982) have found that the majority of the components occupy a limited range in velocity expressed as a fraction of the maximum detected wind velocity, v_e. They find that the component centroid velocity $v_c = 0.74 \pm 0.10 v_e$ for a group of O stars observed in N V and Si IV with *Copernicus.* Prinja and Howarth (1986) also find that low-velocity discrete components are relatively rare among the O stars and B supergiants. Measurement of v_e for Be stars presents some challenges. Unlike the comparatively weakly variable O stellar wind profiles, the resonance profiles of the majority of the Be stars in our sample are dramatically variable. The C IV edge velocity may change by 400–500 km s^{-1} (e.g., 19 Mon) from observation to observation. Table 2 lists the measured v_e and the v_c for the strongest discrete component in selected *IUE* observations of each Be star. It is worth pointing out that studies of individual Be stars (e.g., Doazan *et al.* 1985) have shown that wind profiles totally different from the "typical" configuration can occur. Normalized v_c/v_e data are plotted in Figure 7. A distinctly bimodal distribution is present for our Be stars. The high-velocity peak at $v_c/v_e = 0.8$ is similar to that reported by Lamers, Gathier, and Snow (1982) and may represent a continuation to later spectral types of the discrete-component phenomenon observed in O stars. A significant number of Be stars, including such well-studied objects as 66 Oph, show strong low-velocity or unshifted absorption in excess of that expected from comparison with the normal B stars. As shown in Figure 7, the stars with strong low-velocity components do not differ significantly in spectral type and $v \sin i$ from the other Be stars having discrete components.

We find a threshold in $v \sin i$ for the detection of discrete components in Be stars (see Fig. 1*b*). Shifted discrete absorption components are observed only if $v \sin i \geq 150$ km s^{-1}. Unshifted enhanced absorption, superficially similar to the discrete absorption components, is seen in two stars with $v \sin i = 120$ km s^{-1} and 70 km s^{-1}. In one case (HD 120991) the absorption features are extremely narrow and may not be truly circumstellar. In the other case (HD 78764) the C IV absorption is similar to that seen in the nonradial pulsator ζ Cas. The few *IUE* SWP spectra do not permit us to determine whether this star shows line profile variations similar to those seen in ζ Cas. Similar results for smaller numbers of Be stars with shifted discrete absorption components have been noted by Henrichs (1984). Above this threshold, 78% of the Be stars in our sample show discrete-component absorption in at least one spectrum. Several of the stars with $v \sin i \geq 150$ km s^{-1} not showing discrete components have only a few *IUE* spectra. The lack of detection in some of them may well represent an observational selection effect due to the sporadic and incomplete nature of the *IUE* coverage. We do not find a correlation between the C IV and Si IV equivalent widths and $v \sin i$, in agreement with previous studies (Snow 1981, 1982; BML 1984). The large number of spectra at our disposal, coupled with the published studies of individual stars, make it clear that many, if not all of the Be stars showing component absorption have dramatically variable winds. The intrinsic variability is sufficient to produce the scatter diagrams reported by BML (1984) if only single or small numbers of observations are included in a survey.

BML (1984) suggested that the lack of detection of C IV in low $v \sin i$ Be stars reflected merely the relative scarcity of low $v \sin i$ Be stars. If this were true, and the probability of detecting discrete components were independent of $v \sin i$, we would expect 65% of the low $v \sin i$ stars to show discrete component absorption. For the 11 stars with $v \sin i < 150$ km s^{-1}, this implies detection of discrete components in seven stars. Only two of the stars in our sample show undisplaced enhanced absorption, and none of the stars show shifted discrete components. Many of the high $v \sin i$ Be stars have shown strong winds despite having been observed only a few times. The majority of the low $v \sin i$ (<150 km s^{-1}) Be stars have been observed as frequently as the average higher $v \sin i$ Be star. We feel that this result is not due to an observational selection effect, but reflects intrinsic differences in the structure of the atmospheres in the lines of sight to the low $v \sin i$ Be stars. The deficit of strong-wind and discrete-component detections in these stars suggests that strong-wind episodes characterized by the presence of highly ionized material such as C IV are either not present, or do not occur as frequently as in the higher $v \sin i$ Be stars, or that the material forming the discrete components is not present in the lines of sight through these stellar atmospheres. This topic will be pursued, together with implications for models of Be stellar atmospheres, in § VII below.

We find some suggestion of a luminosity dependence in the presence of highly ionized discrete components at the cool end of our sample interval. At B5 none of the dwarf stars in our sample have been observed to have discrete components, while the two giant stars frequently show such features. Inspection of Figure 2 in BML (1984) suggests that C IV absorption is extremely rare in Be stars later than B5, and that of the seven B5–B7 stars showing C IV absorption, four are luminosity class III. Confirming the relative scarcity of discrete component absorption in luminosity classes V and IV at B5 and later spectral types will require acquisition and examination of additional spectra and will be covered in a separate study.

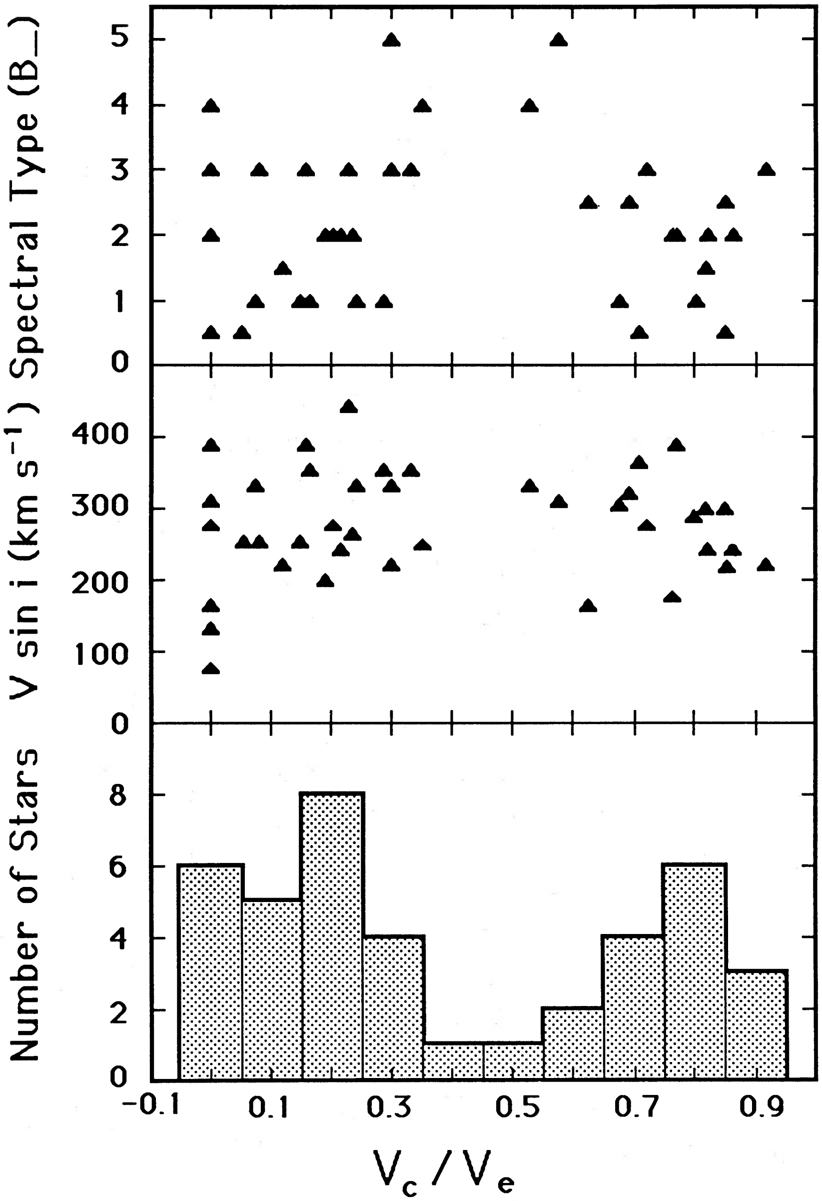

FIG. 7.—Distribution of centroid velocity of strongest discrete component normalized to maximum velocity detected in wind. Distribution of components as function of spectral type (*upper*), *v* sin *i* (*middle*), and a histogram (*lower*).

V. DISCUSSION

a) *Be stars and Radiatively Driven Stellar Winds*

Be stars generally lie below the region in the H-R diagram where radiation pressure alone is believed to be sufficient to drive a strong stellar wind (Abbott 1982). Previous studies of Be winds have attempted to assess the importance of radiation pressure by studying the dependence of the maximum wind velocity or mass-loss rate on spectral type, or, equivalently, on stellar luminosity (Snow 1981, 1982), and have found that a similar relation between stellar luminosity and mass-loss rate, determined by assuming spherical symmetry in the wind, holds for both Be and the more luminous OB stars studied by Garmany *et al.* (1981). Considerable scatter from the relation noted by Snow is present, and the derived relation may represent an upper envelope. More recent studies of Be atmospheres (Oegerle and Polidan 1984) have questioned the assumption of spherical symmetry in Be stellar winds. Another objection is that comparison of C IV and Si IV profiles for many of the stars in our sample shows that the discrete components which dominate the C IV profile tend not to be as obvious in Si IV as in C IV. In many cases when discrete components are easily seen in C IV, only blended, enhanced absorption producing an asymmetric profile is found in Si IV. Snow's (1982) analysis of the mass-loss rates assumed that Be stellar winds could be modeled in the same way as O star profiles. The model he used, due to Castor and Lamers (1979), assumes steady state mass loss from a nonrotating star, and does not treat discrete components.

The importance of radiation pressure in Be winds can also be assessed by looking for correlations between wind strength and the variable stellar-continuum flux. While this approach cannot be used for much of our data since the *IUE* spectra are a mixture of small- and large-aperture observations, some stars, such as 59 Cyg (Doazan *et al.* 1985), 66 Oph (Grady *et al.* 1987*a*), ω Ori (Sonneborn *et al.* 1987), and λ Eri (Barker 1986) have been monitored regularly with the large aperture. Significant changes (>10%–15%) in the continuum from 1200 to 1950 Å have not been observed for these stars. This result does not rule out changes in the flux at shorter wavelengths. *Voyager* UVS observations of 66 Oph (Peters and Polidan 1987) have shown that changing far-ultraviolet flux levels shortward of 1200 Å are present, and are apparently anticorrelated with the stellar wind strength. More observations are required, both of this star and of other Be stars in order to determine whether such flux variability is a general property of these stars. The origin of the changing far-ultraviolet flux distribution is currently uncertain. It may be due to changing far-ultraviolet opacity in the outer atmosphere, such as might be provided by variations in the atmospheric density, resulting in an anticorrelation between the resonance-line absorption and the flux levels. Alternatively the changing fluxes may be caused by changing stellar T_{eff} and possibly by changing radius. Similar changes have been invoked to account for the far-ultraviolet flux variations in β Cep stars (e.g., BW Vul; Barry *et al.* 1984). In either case, the anticorrelation between wind strength and far-ultraviolet flux would be consistent with the expected behavior of a radiatively driven wind.

An alternative approach for assessing the importance of radiation pressure in driving Be-stellar winds is to look for a correlation between v_e and the estimated escape velocity (v_{esc}) from the photosphere. As shown in Garmany (1984), v_e/v_{esc} ranges from values of 2–3 for O stars, down to 1.0 and below for B supergiants. Values of v_e/v_{esc} between 1.0 and 1.5 are consistent with single scattering radiative acceleration (Abbott 1982), whereas values in excess of 1.5 indicate the presence of multiple scattering in the stellar atmosphere, in the limit that the star is treated as an illuminating point source. The recent work of Pauldrach, Puls, and Kudritski (1986) shows that considerably higher values of v_e may be achieved if the geometry of the star is handled more realistically. Nevertheless, values of v_e/v_{esc} below 1.0 indicate that while material may be lifted above the stellar photosphere, its loss from the system cannot be guaranteed without additional information on the wind velocity law. Using estimates of v_{esc} from Underhill and Doazan (1982) for luminosity class IV and V stars, the majority of our Be stars have v_e/v_{esc} from 0.5 to 1.0 and the overall trend is similar to that shown by Garmany (1984) for B supergiants, but occurring at lower relative velocities (Fig. 8). The only luminosity class IV–V stars showing $v_e/v_{\mathrm{esc}} > 1.5$ are γ Cas, o Pup, and V 1294 Aql. The majority of the earlier Be stars show v_e/v_{esc} in the range 1.0–1.5 which is consistent with radiative acceleration of the wind material *once the wind is initiated.* Mass loss from the winds in the later Be stars is more problematical.

Our data suggest that while radiation pressure may be a factor in driving Be stellar winds, it is not the only factor. The presence of alternating strong and B-normal wind episodes in 11 Be stars in our sample also suggest that nonradiative effects are important in generating strong and highly variable winds in these stars. The relative dominance of the discrete components and the existence of "favorite" component velocities in individual Be stars, first noted by Peters (1982*b*, *d*) also argue for a nonradiative factor in Be winds. The most promising possibilities for such nonradiative factors are those depending upon those characteristics of Be stars which differentiate them from the normal B stars.

b) The Connection with Stellar Pulsation

Recent work has shown that many, if not all, Be stars show evidence for short-term variations in their photospheric line profiles. Model fits to these profile changes indicate that characteristic pulsation modes are present which distinguish the Be stars from normal B stars (Percy 1985; Smith and Penrod

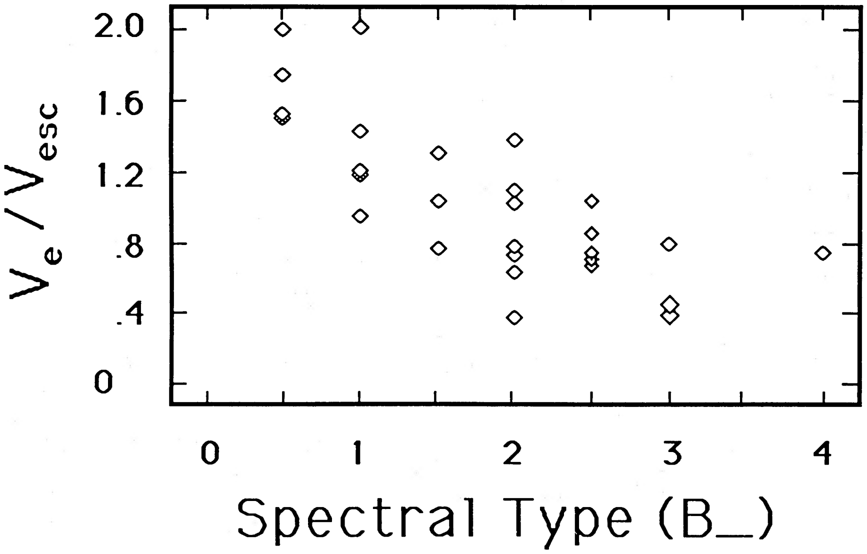

FIG. 8.—v_e/v_{esc} for luminosity class V–IV Be stars as function of spectral type

1985; Henrichs 1986*a*). An important question is whether pulsation is closely associated with the other atmospheric phenomena, including the highly ionized winds. The available data permit us to evaluate the importance of pulsation in two ways: comparison of the Be stellar winds with winds in other pulsating B stars, and evaluation of the pulsation characteristics of a large sample of B stars. The second approach will be treated in § VI*e*.

Our normal B-star sample contains several stars which have been identified as β Cep stars. These objects are believed (Lesh 1982) to be radial pulsators. Only two studies have been made of wind variations on time scales longer than the pulsation period in these stars, and only for the prototype, β Cep. Fahey, Fischel, and Sparks (1982) and Fischel and Sparks (1980) found that β Cep's wind shows ionization similar to that detected in the Be stars. Periodically enhanced resonance profiles are also present. Continuum variability could not be assessed since the spectra were obtained with the small aperture. Inspection of the profiles shows that the dominant, and variable, feature is a discrete absorption feature at zero velocity. At wind maximum enhanced high-velocity absorption is also present. The overall appearance of the profile at maximum is similar to the wind maximum profiles observed in 66 Oph, with the strongest absorption at zero velocity rather than at -200 km s^{-1}. Similar variability is seen in two of the B stars in our sample, ζ Cas and σ Lup. *IUE* observations over time scales longer than the pulsation period are not available for the other β Cep stars in our sample.

Our B-normal star sample also contains the prototypical star, 53 Per, interpreted by Smith (1977) as a nonradial pulsator. Like the β Cep stars, this object has a low $v \sin i$. Unlike the β Cep stars, it shows little or no suggestion of variations in the resonance lines of C IV, Si IV, or Si III.

Ten of the Be stars in our sample (HR 2855, π Aqr, P Car, 27 CMa, HD 78764, HD60855, HD 120991, μ Cen, η Cen, and a single spectrum of 59 Cyg) have shown strong, undisplaced, or extremely low velocity absorption similar to the shortward-shifted discrete components, and also similar to the zero-velocity features in the β Cep stars. The extremely low velocity absorption occurs over the entire spectral range of our survey. Two of the stars showing zero-velocity features have $v \sin i < 150$ km s^{-1}, where discrete-component absorption is not otherwise observed. These stars have spectral types similar to those of the β Cep stars in our normal star sample. Seven of these objects have undisplaced discrete-component absorption in all of the available *IUE* spectra. These stars, except for 59 Cyg, have not been observed to alternate between strong- and weak-wind phases. Five of these stars have shown strong high-velocity absorption in addition to the low-velocity or unshifted components.

While Be, β Cep, and 53 Per stellar winds have some similarities, there are also some important distinctions. The β Cep stars have typically low values of $v \sin i$, whereas the Be stars with strong stellar winds tend to have $v \sin i \geq 150$ km s^{-1}. Be stellar winds show superionization to later spectral types, and have winds reaching higher velocities and larger equivalent widths than either the β Cep stars or the 53 Per stars. Discrete components, including the zero-velocity features, are seen in only the β Cep stars and the Be stars. As indicated by 59 Cyg (Doazan *et al.* 1985), 66 Oph (Grady *et al.* 1987*a*), ω Ori (Sonneborn *et al.* 1987), and other Be stars, no single period appears to characterize the alternation between strong- and weak-wind episodes in Be stars. Fahey *et al.* (1982) have shown that the variations in β Cep have a period of 6.1 days. It remains to be determined whether other β Cep stars show periodically variable winds. If however, we assume that the presence of a pulsating photosphere is important in triggering the discrete components in both β Cep and Be stars, while not producing similar behavior in the 53 Per stars, it is tempting to ascribe the differences in the wind characteristics to differences in pulsation characteristics.

One possible cause for the differences in wind strength between the β Cep stars and the Be stars, if pulsation is important in causing the formation of discrete components, may be that the rapid rotation of the Be stars selects which pulsation modes are excited. For example, Smith and Penrod (1985) have suggested that the rapid rotators pulsate in modes in which most of the pulsation energy goes into higher amplitude surface motions which are likely to trigger outflow. Smith and Penrod (1985) estimate that a mass loss comparable to that typically estimated for Be stars (10^{-11} to 3×10^{-9} $M_{\odot}$ yr^{-1}; Snow 1981) may be produced by nonradial pulsations in early-type B stars. Another interesting aspect of the Smith and Penrod (1985) model is that it allows B stars to have both B-normal and Be phases, depending upon the mode switching of the pulsations. This may be a promising way of explaining the variable wind strengths and recurrent wind episodes observed in several moderate to high $v \sin i$ Be stars. This is clearly a question of great interest, in need of further theoretical and observational pursuit.

In contrast to the β Cep stars, the 53 Per stars, and the majority of Be stars, several of the stars with either undisplaced or relatively low-velocity discrete components (48 Lib, ϵ Cap, P Car, 27 CMa, and HR 2855) have emission in the most highly ionized wind species. HR 2855 and 27 CMa show emission in N V and, more weakly, in C IV. In HR 2855 the N V emission is clearly variable. In 27 CMa, the strength of the zero-velocity feature in N V and its variability preclude evaluation of N V emission changes. Variable C IV emission has been observed in ϵ Cap, P Car, and 48 Lib. Strong C IV emission is seen only in the interacting binary systems, φ Per and ζ Tau, which are believed to be viewed nearly equator-on. The similarity of the absorption and emission profiles in these other Be stars, together with the presence of emission, implies that these objects may also be viewed close to edge-on to the equatorial plane. The dearth of emission in other Be stars can then be interpreted as simply an inclination angle effect, with the stars not showing emission viewed at somewhat higher latitudes.

VI. COMPARISON WITH OTHER SPECTRAL REGIONS

a) Optical Polarimetry

Many Be stars are known to show both significant and variable continuum linear polarization in the optical. Poeckert and Marlborough (1978) and McLean and Brown (1978) found that low $v \sin i$ Be stars tended to show only small intrinsic polarization, whereas Be stars with $v \sin i > 150$ km s^{-1} showed a wide range of detected polarizations. Small values of linear polarization are to be expected if the material responsible for the polarization is in the form of a disk viewed nearly pole-on. The largest values of polarization are expected when a disk is viewed edge-on. Variations in disk density, which are believed to be responsible for variable polarization in some Be stars (Hayes and Guinan 1984; Guinan and Hayes 1984), can account for much of the scatter in their diagram. Two of the stars in our sample, ω Ori (Sonneborn *et al.* 1987) and 66 Oph (Grady *et al.* 1987*a*), have contemporary optical-polarization measurements and *IUE* spectra. No correlation has been found between the strength of the highly ionized stellar wind and the polarization, or between the polarization episodes and the wind variability. This lack of correlation is interpreted as evidence that the highly ionized stellar wind in these stars occurs above the continuum-polarization formation region. This geometry is similar to that inferred from evaluation of the wind emission in some Be stars.

b) *Infrared*

Waters (1986*a*) in a survey of both B and Be stars observed with the *IRAS* satellite and detected at 12 μm, found that not only is a large intrinsic color excess found for the Be stars, but that low $v \sin i$ B dwarfs from B0–B4 tended to show only small color excesses, with the fraction of all B stars showing large color excesses increasing with $v \sin i$. For B5–B9.5 stars he found small color excesses for $v \sin i < 200$ km s^{-1}, and a range of excesses for $v \sin i > 200$ km s^{-1}. The $v \sin i$ data in his survey was drawn from the Bright Star Catalog (Hoffleit 1982), which may account for the higher threshold than we observe in the UV, drawing the $v \sin i$ data primarily from Slettebak (1982). For the Be stars as a group, however, the correlation of the 12 μm IR excess with $v \sin i$ is not clear, since limiting the comparison to Be stars strongly biases the sample to high $v \sin i$ and high IR excess (Cote and Waters 1986).

c) Hα

Since emission in the Balmer series, most notably in Hα, is the defining characteristic of Be stars, it is natural to compare the highly ionized winds observed in the ultraviolet with both the strength and shape of the Balmer emission-line profiles. BML (1984) compared the C IV equivalent widths from their sample of northern Be stars with contemporary Hα equivalent width data. They found no correlation between the strength of the Hα emission and the C IV strength. Inspection of the catalogs of Dachs *et al.* (1981), Andrillat and Fehrenbach (1982), and Andrillat (1983), together with published Hα data (Barker 1982, 1983, 1984; Doazan *et al.* 1985) indicates that the Be stars with $v \sin i < 150$ km s^{-1} tend to have single or relatively narrow emission profiles, whereas the higher $v \sin i$ stars have broad, double, or asymmetric emission (Figs. 9*a*–9*c*). Similar conclusions have been reached by Dachs *et al.* (1986). Comparison of our sample of Be stars with the published Hα catalogs shows that the Be stars having shortward-shifted discrete components tend to have broad, asymmetric or double Hα profiles. Some stars having narrow Hα emission profiles do show strong stellar winds (e.g., 105 Tau), and Be stars with double Hα emission profiles later in spectral type than B5 tend not to show C IV absorption, so the separation is not totally clearcut. At present, insufficient contemporary UV and optical data has been assembled for a large enough sample of Be stars to determine whether the profile shape characteristics in Hα provide an indication of the strength of Be winds, although such a relation was observed in the V/R ratio in Hα in 59 Cyg (Doazan *et al.* 1985).

d) Fe II

Slettebak's (1982) catalog of Be stars contains notes on both Hα and Fe II emission and absorption characteristics. While the Fe II data is not quantitative, it can still be compared with the ultraviolet characteristics of our program stars. Of the 11 Be stars in our sample with $v \sin i < 150$ km s^{-1}, five are noted as showing no Fe II emission in 1979–1980, five stars are described as having "single" or "narrow" emission, and one star is not cataloged by Slettebak. Above $v \sin i = 150$ km s^{-1} the picture is somewhat different. Of the 51 remaining stars in the sample, 20 stars have no mention of Fe II, three stars are stated to have no Fe II emission, nine stars are described as having "emission," 16 stars as having double emission, two stars (48 Lib and EW Lac) show shell absorption in Fe II, and four stars are not cataloged by Slettebak. It is interesting to note that double emission-line profiles are apparently not seen in Fe II below 150 km s^{-1}, whereas they are quite common above that $v \sin i$. As with the Hα data, however, apparently a wide range in Fe II emission strength is observed.

e) *Pulsation Characteristics of Be Stars*

Several of the Be stars in our sample have been identified as nonradial pulsators either from photometric variability (Percy 1985), or from analysis of photospheric line profile variations (Penrod 1986; Smith and Penrod 1985). While the sample of Be stars with detections of pulsation is incomplete, enough stars have been observed to note that pulsation is seen over a wide range in $v \sin i$. Smith and Penrod (1985), in an analysis of the available data on Be stars, found that Be stars with $v \sin i < 150$ km s^{-1} show prograde pulsation modes, whereas those with $v \sin i \geq 150$ km s^{-1} show retrograde modes. In view of the change in infrared, continuum polarization, Hα and Fe II profile shapes, and wind characteristics at essentially the same $v \sin i$, we feel that this datum presents the strongest evidence currently available for the association of pulsation properties and the presence of the Be phenomenon.

VII. THE EVIDENCE FOR ASPECT-DEPENDENT WINDS IN Be STARS

The available ultraviolet, optical, and infrared data suggest that the outer envelopes of low $v \sin i$ Be stars differ from those seen in higher $v \sin i$ stars. Below 150 km s^{-1}, only weak stellar winds are observed, continuum polarization is minimal, the optical emission lines tend to be comparatively narrow and do not show double emission profiles, and infrared excesses are relatively small. Above this $v \sin i$, strong and highly variable winds are observed, a large range in continuum polarization is observed, the optical emission lines are frequently double or broad, and infrared excesses show a larger range. The interpretation of these data rests on the interpretation of the $v \sin i$ data for Be stars. If the assumption is made that low $v \sin i$ Be stars, as a class, correspond to the most slowly rotating Be stars, and higher $v \sin i$ Be stars correspond to more rapidly rotating Be stars, the inescapable conclusion is that rotation is important in determining the characteristics of the outer atmospheres of these stars. The major difficulty of this interpretation is that it is necessary to postulate additional mechanisms to distinguish the low $v \sin i$ Be stars from other slowly rotating and pulsating B stars such as the 53 Per stars.

If however, the assumption is made that Be stars, as a class, form a population of rapidly rotating B stars with some unknown range in equatorial velocity, and viewed at a variety of inclination angles, the low $v \sin i$ stars may be interpreted as the Be stars which are viewed at relatively high latitudes. This interpretation is not new and has resulted in some low $v \sin i$ Be stars being designated "pole-on." Since we do not know the range in equatorial velocity for Be stars, we prefer to adopt a more conservative approach. Under this interpretation, higher $v \sin i$ Be stars are likely to be those viewed at lower latitudes. Recent studies of shell absorption features in Be stars (Oegerle

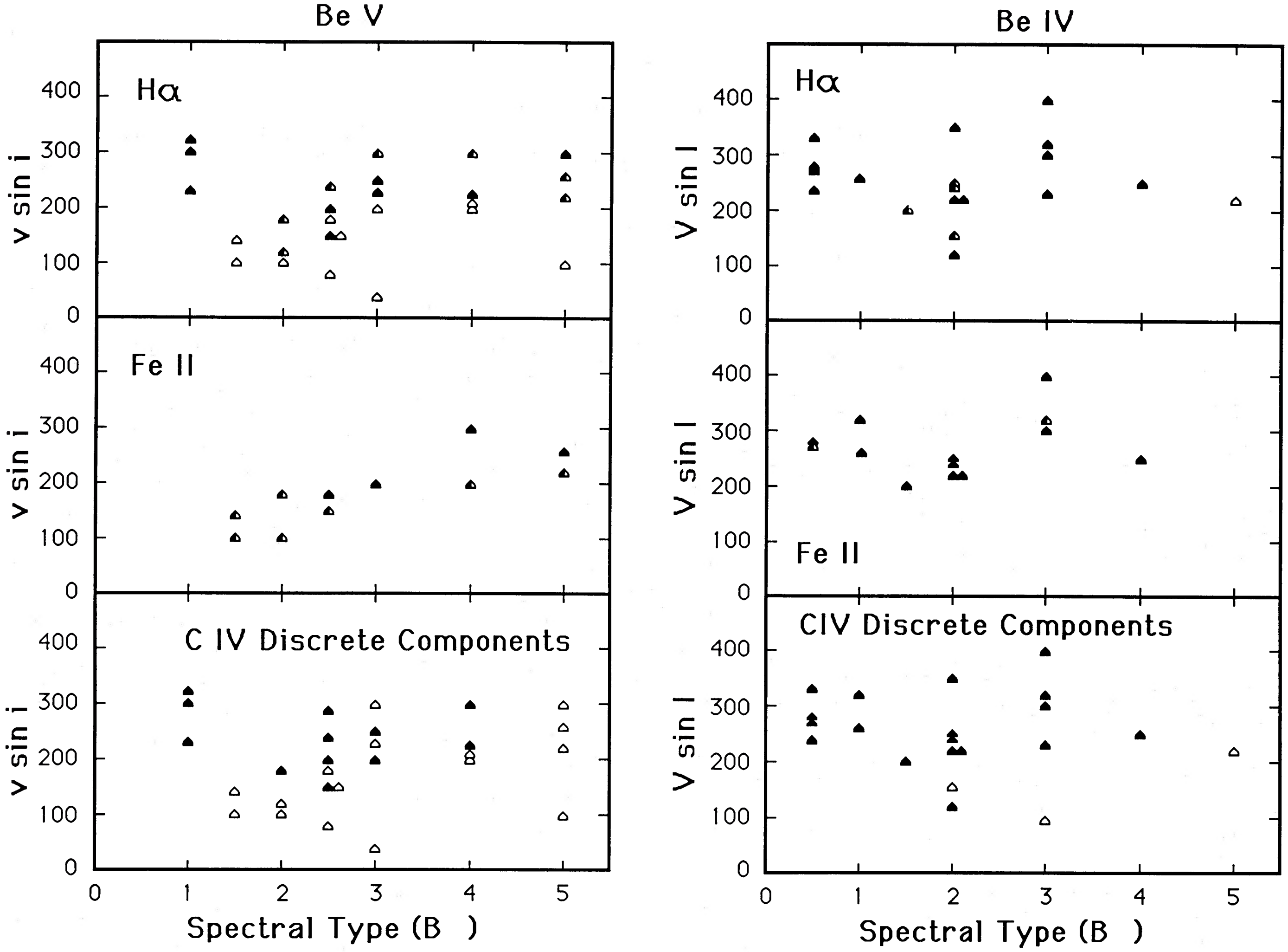

FIG. 9*a*

FIG. 9*b*

FIG. 9.—Comparison of Hα emission profile shape, presence of Fe II in emission or absorption, and detection of discrete components by luminosity class. Upper panels show Hα emission characteristics of sample Be stars: filled symbols indicate double emission profiles; partially filled symbols indicate broad, single emission; and open symbols indicate narrow emission profiles). Hα data from Dachs *et al.* (1981), Andrillat and Fehrenbach (1982), Andrillat (1983), and Barker (1982, 1983, 1984, 1985). Note that perfect correlation between Hα emission profile shape and C IV characteristics is not expected for all stars because of intrinsic variability of both lines, and lack of simultaneous UV and optical data. Central panels show Fe II characteristics for each star with Fe II notations in Slettebak (1982). Filled symbols indicate double emission profiles; partially filled symbols indicate single emission profiles. Discrete components in C IV denoted by filled symbols in lower panels. (*a*) Luminosity class V Be stars. (*b*) Luminosity class IV Be stars. (*c*) Luminosity class III Be stars.

and Polidan 1984) have also suggested a cylindrical or disklike geometry for Be stars. Such a geometry is consistent with the available polarimetric data and can also account for the infrared excess data (Waters 1986*b*).

The stars showing more or less permanent shell spectra, many of which have relatively high *v* sin *i*, even for Be stars, may be those which are viewed near the equatorial plane. These stars are characterized during shell episodes as having Hα profiles with double emission and strong central reversals. Typically these stars show some C IV absorption, but it is comparatively weak and of low velocity. These stars also differ from other Be stars by having the strongest evidence for emission in C IV. Four of these stars, 48 Lib, HR 2855, ϵ Cap, and P Car have variable weak C IV emission. The presence of emission suggests eigher that the winds in these objects are more extended than in "normal" Be stars, or that a substantial portion of the highly ionized wind does not lie in the observer's line of sight. Oegerle and Polidan (1984) have concluded that ultraviolet shell absorption features in some of these stars are consistent with the stellar atmospheres in these objects having cylindrical symmetry, and the stars being viewed edge-on, or close to edge-on, to a disk. If this geometry is correct, the wind in the disk plane may be sufficiently dense that radiative acceleration to high velocity is not possible, and that the overall ionization level in the equatorial plane remains relatively low. Higher ionization stages and/or higher velocities might be detectable in the less dense portions of the wind, occurring primarily at higher latitudes, and thus produce C IV or even N V emission.

VIII. IMPLICATIONS FOR MODELS OF Be STARS

The data we have presented, particularly the deficit of strong winds and discrete components in low *v* sin *i* Be stars, together with the presence of weak emission in stars showing shell spectra, have implications for several of the models proposed for Be stars. The "planetary nebula" model, initially proposed

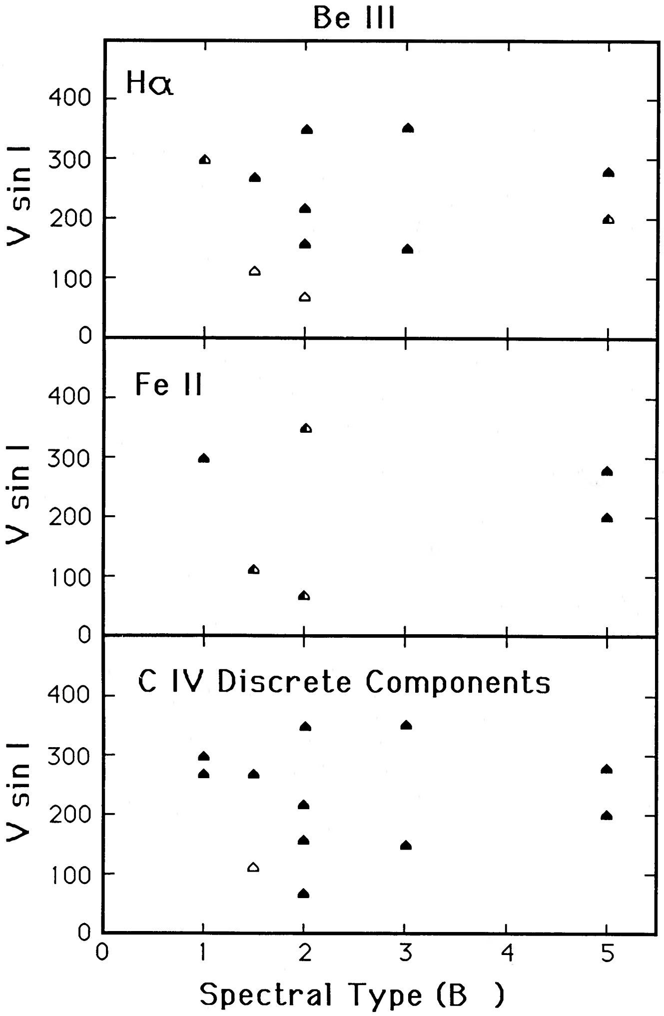

FIG. 9c

to reconcile the presence of highly ionized and high-velocity winds with the presence of a low-velocity and cool circumstellar envelope by Doazan, Kuhi, and Thomas (1980) assumes that the highly ionized and cool portions of the circumstellar envelope occur at all latitudes, but are separated in radius. The weakness of emission in the UV resonance lines is interpreted in this model as suggesting that the highly ionized wind occurs close to the photosphere, while the Hα emission is produced at larger radii. The radial structure assumed in this model, together with the observation of only low-velocity emission in Hα, implies the existence of a wind deceleration zone at larger radii than the wind acceleration zone. Recent extensions of the model (Doazan 1987) have relaxed the initial assumption of spherical symmetry and now allow some degree of flattening of the stellar envelope to be consistent with the presence of significant linear polarization in Be star spectra. Doazan (1987) predicts that the degree of flattening, and the strength of the highly ionized stellar wind should not be correlated with $v \sin i$. The model predictions are inconsistent with the absence of strong and highly variable winds in Be stars with $v \sin i < 150$ km s^{-1}, together with thresholds in the other data sets, particularly the linear polarimetry.

Several other models have been proposed to account for the presence of discrete-component absorption in the winds of both O and Be stars. The corotating interaction region (CIR) model proposed by Mullan (1984, 1986) for O stars interprets the discrete components as features produced by the interaction of fast- and slow-moving streams in the stellar wind. This model may not be totally appropriate to Be stars since it assumes that a steady state stellar wind should be detectable. Such a wind is generally not seen in our stars with spectral types of B2 and later. The model predicts that the component centroid velocity, v_c, should occur at lower velocities relative to the wind terminal velocity as the stellar equatorial velocity increases. This corresponds to smaller values of v_c/v_e as $v \sin i$ increases. We do not observe such a relation in our sample of Be stars. The model also cannot account for the presence of a threshold in wind and envelope characteristics at approximately $v \sin i = 150$ km s^{-1}. The magnetically constrained wind model of Underhill and Fahey (1984) has difficulties with the production of long-lived components which are essentially invariant in radial velocity, and which recur episode after episode (as seen in 66 Oph). This model likewise cannot account for a threshold in envelope characteristics at $v \sin i = 150$ km s^{-1}. The shell-ejection scenario of Henrichs *et al.* (1983) requires an additional mechanism for triggering the formation of the shell, and cannot account for a threshold in the detection of shortward-shifted discrete components at $v \sin i = 150$ km s^{-1}, with the observation of wind episodes, and with the presence of characteristic velocities for discrete components in particular stars. The recent Poe and Friend (1986) magnetic-wind model does not address discrete components at all, although the equatorially concentrated mass loss which their model predicts may be consistent with our data. The earlier Poeckert and Marlborough (1978) model predicts a similar wind geometry, but fails to account for the presence of wind variability and discrete components. The multiple-shock wind described by Barker (1987), and based upon the work of Lucy (1984) for O stars, can account for wind absorption in the form of discrete components, but is not yet capable of tackling the issues of wind episodes, or of thresholds in $v \sin i$ for wind characteristics.

As noted by Henrichs (1986*a*), the available wind and envelope models for Be stars have difficulty in accounting for the presence of discrete-component absorption. Our data aggravate this difficulty by imposing the additional constraint of detectability of the shortward-shifted components if and only if $v \sin i \geq 150$ km s^{-1}. We feel that currently the most promising approach may be provided by the incorporation of pulsation data, together with spectral data from the far-ultraviolet through the infrared, into wind models with an equatorial concentration of mass loss. Much work will be required before any such models may be compared with the available data, or can be expected to be tested with new observations.

IX. SUMMARY

Excess wind absorption in Be stars over that detected in normal B stars is found in C IV and Si IV, confirming results of previous surveys. Similar results are found at lower significance in N V for the earliest Be stars in our sample. The stars showing excess wind absorption tend to be those stars showing one or more discrete absorption components. This result, together with previous studies of individual Be stars, suggests that much, if not all, of the excess wind absorption is in the form of discrete absorption components. Excess and variable wind absorption is also reported for one previously known β Cep star among our normal B stars, and for one star, σ Lup, which has not previously been reported as having a variable stellar wind.

The C IV edge velocity is not a well-defined quantity for many of the Be stars in our sample, but depends rather critically on the distribution of discrete absorption components in the resonance profile. The upper envelope of edge velocities shows an overall trend of decreasing toward later spectral types, although considerable scatter is observed, preventing prediction of edge velocities as a function of spectral type, $v \sin i$, or luminosity class.

Unlike discrete components in many O stars, the distribution of the strongest discrete component normalized to the edge velocity shows a clearly bimodal distribution. One peak is seen near $v_c/v_e = 0.8$, and appears to be similar to the peak in O star components at 0.74 reported by Lamers, Gathier, and Snow (1982), and similar features reported by Prinja and Howarth (1986). The other peak occurs at 0.2 and appears to be relatively uncommon among O stars. Stars having strong low-velocity absorption include such well-studied objects as 66 Oph and 28 Cyg. Seven of the Be stars in our sample have shown strong undisplaced absorption in at least one spectrum. Six of the seven stars show undisplaced or extremely low-velocity absorption in the majority of their spectra. The closest analogs to the resonance profiles of these stars are found in the β Cep stars, several of which have been included in our population of "normal" B stars.

We find a threshold in $v \sin i$ and the presence of enhanced wind absorption and/or discrete components. Shifted discrete absorption components are observed only if $v \sin i \geq 150$ km s^{-1}, confirming the results of the smaller survey by Henrichs (1984). Unshifted enhanced absorption is seen in only two stars with $v \sin i < 150$ km s^{-1}. Above 150 km s^{-1}, 77% of the stars show shifted discrete absorption components in at least one spectrum. Above the 150 km s^{-1} threshold, no correlation is seen between the strength of absorption and $v \sin i$. As demonstrated by studies of individual Be stars, the absence of any correlation is at least partly due to the intrinsic variability of the winds in these objects. Similar cutoffs as a function of $v \sin i$ have been noted in *IRAS* color excesses of B stars (Waters 1986), and in polarimetric surveys (McLean and Brown 1978). Below ~ 150 km s^{-1}, Hα tends to show narrow single emission profiles (as also noted by Dachs *et al.* 1986). Fe II emission, when present, tends to be described as narrow (Slettebak 1982). Above 150 km s^{-1}, Hα profiles are frequently broad and double. Double Fe II emission is also common and single emission profiles much less common.

Collectively these results imply either that low $v \sin i$ Be stars have fundamentally differently structured outer atmospheres than do higher $v \sin i$ Be stars, while still producing observable Hα emission, or that the outer atmospheres of these objects are not spherically symmetric and the character of the spectral signatures of the Be phenomenon is a function of the viewer's inclination angle. If the former interpretation is accepted, some factor other than the stellar rotation must be responsible for the dramatic differences between low $v \sin i$ Be stars and other low $v \sin i$ (but pulsating) B stars such as the 53 Per stars. Rotation can certainly account for the difference between low $v \sin i$ and higher $v \sin i$ Be stars in this scenario. If, however, the latter alternative is accepted, the resulting geometry of minimal winds at high latitudes, due to the relative sparsity of material lost in the polar regions, and of strongly variable and highly ionized winds at intermediate latitudes, with dense and less highly ionized material near the equator, is the sort of geometry expected if both rotation and, possibly, nonradial pulsation are important in ejecting material from the star.

Additional observational work is needed before the importance of nonradial pulsation on Be stars can be considered proven. One important avenue of attack will be the determination of whether or not pulsational properties in a few carefully selected Be stars change in concert with the changing winds. The importance of a changing photospheric radiation field, and hence the effects of radiation pressure in Be atmospheres, can properly be assessed only when additional far-ultraviolet data are available. An observing program to obtain some of these data is currently underway with monthly optical, polarimetric, and ultraviolet monitoring supplemented by *Voyager* UVS observations. Similarly, additional polarimetric, optical and infrared monitoring of these stars will be needed to constrain the wind geometry further. Considerable effort will be needed in order to assimilate the increasing amount of data available on Be stellar atmospheres and to interpret these objects in the context of our understanding of early-type stars. It is our hope that this survey may further our understanding of Be stars and early-type stars in general.

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