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HIGHLY IONIZED STELLAR WINDS IN Be STARS. II. WINDS IN B6–B9.5e STARS

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ABSTRACT

We present the results of an ultraviolet survey of stellar winds and circumstellar shells in 40 B6–B9.5e stars covering luminosity classes V–III. We find a continuation of the $v \sin i$ threshold for the tection of C IV reported in 1989 by Grady, Bjorkman, and Snow, with C IV detected only in luminosity class V stars with $v \sin i > 200$ km s^{-1}, and in luminosity class IV–III stars with $v \sin i > 140$–160 km s^{-1}. Narrow absorption cores in the excited state line of Si II λ1533.4, which are indicative of the presence of a cool circumstellar envelope or "shell," are found in several of the program stars. With the exception of HD 23630, all of the detections occur in stars with $v \sin i \geq 200$ km s^{-1}. Comparison of the ultraviolet data with published infrared color excesses, optical polarization data, and optical line profile atlases shows that these data sets have similar thresholds in the vicinity of 150–200 km s^{-1}, indicating that the Be phenomenon in B6–B9.5e stars is similar to that observed in hotter and more luminous stars. The C IV absorption in nine of the program stars is produced in one or more shortward-shifted discrete absorption components, similar to those seen in earlier type Be stars. Three of the program stars have shown unambiguous variability in C IV in the course of *IUE* monitoring, suggesting that the highly ionized material is produced in a stellar wind.

Subject headings: stars: Be — stars: rotation — stars: winds — ultraviolet: spectra

I. INTRODUCTION

Ultraviolet and infrared observations of Be stars have shown that these objects have mass-loss rates as much as several orders of magnitude greater than those of normal B stars of comparable spectral type and luminosity class (Lamers and Waters 1987). Since the majority of Be stars are insufficiently luminous to have stellar winds initiated by radiation pressure on the photosphere (Abbott 1982) and a distinguishing characteristic of Be stellar winds is temporal variability, some other mechanism must produce these stellar winds. Bjorkman and Snow (1988*a*) have also reported evidence for a second mechanism on the basis of *IUE* observations of *IRAS*-selected Be stars. A first step toward identifying the mechanism(s) is to determine for which combinations of effective temperature, luminosity, and rotational velocity stellar winds are detected. This strategy has been used by Snow (1982), Barker, Marlborough, and Landstreet (1984), and Henrichs (1984) in surveys of Be stellar winds. The Snow (1982) and Barker, Marlborough, and Landstreet (1984) surveys contained limited numbers of stars, and typically only single observations of each star. No correlation of wind properties with any parameters were found by these surveys. Henrichs (1984), in a survey of a smaller number of stars, but including more spectra of each star, did find a suggestion that wind detections were restricted to the higher $v \sin i$ stars.

More recently, Grady, Bjorkman, and Snow (1987, hereafter Paper I) found that the detection of wind absorption in the ultraviolet resonance lines of C IV, N V, and Si IV in B0.5–B5e stars showed a threshold at approximately 150 km s^{-1}, with stars having $v \sin i > 150$ km s^{-1} showing winds in approximately 77% of the stars. Their sample of 62 Be stars suggested that the threshold might increase with decreasing effective temperature, especially for the luminosity class V stars at B4 and B5. They also found that the $v \sin i$ threshold for wind detections corresponds to the threshold for the detection of significant linear polarization, significant *IRAS* 12 μm color excesses, the onset of double- or broad-line profiles in Hα, and changes in the dominant nonradial pulsation modes observed in the Be stars. Taken collectively these results implied that *both* rotation and pulsation were likely to be important in producing the Be phenomenon. An important test of this hypothesis is to determine whether other Be star populations exhibiting similar thresholds for infrared excesses and Hα profile shapes also show a wind detection threshold at the same $v \sin i$. The later

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Be stars, which were not included in Paper I, but which have been extensively monitored in the optical and have published *IRAS* fluxes, are an ideal population to test this hypothesis.

Comparatively few B6–B9.5e stars have published UV data. The only systematic survey of winds in late-type Be stars, By Slettebak and Carpenter (1983), included only seven B6–B9.5e stars. Slettebak and Carpenter did find a suggestion that the strength of any wind features increased with $v \sin i$ but had too few stars to separate luminosity effects from rotation. In the 4 years since the Slettebak and Carpenter survey, additional observations of B6–B9.5e stars have been made with the *IUE*. The increase in both the numbers of stars observed and in the number of spectra available for specific stars has prompted us to make a more extensive survey of stellar winds in properties among the late-type Be stars.

II. PROGRAM STAR SELECTION CRITERIA

We have restricted our survey to B6–B9.5e stars in luminosity classes V–III in order to exclude supergiant stars which retain strong stellar winds as they evolve away from the ZAMS. This range in luminosity class corresponds to the "classical" definition of Be stars. In order to have *IUE* high-resolution spectra with moderate to high signal-to-noise ratios, and to have stellar spectral type, luminosity class, and $v \sin i$ data which are directly comparable with the Paper I data, we have largely restricted our attention to bright Be stars with $V < 6.0$ and $v \sin i$ from Slettebak's (1982) survey. We have attempted to have stars spanning a range in $v \sin i$ at each spectral subtype and luminosity class. Figure 1 shows the distribution of our program stars in spectral type, luminosity class, and $v \sin i$. Despite the research interests of *IUE* observers, particularly the recent focus on Be stars with *IRAS* 12 μm color excesses, the available program stars are distributed in $v \sin i$ very closely to the distribution of stars in Slettebak's (1982) catalog. The mean $v \sin i$ for the B6–B9.5e stars in Slettebak's catalog is 228, while the mean for our sample is 226 km s^{-1}. Slettebak's catalog contains 55 stars from B6 to B9.5. Our sample contains 40 Be stars and consists of 86% of the stars in Slettebak's catalog at B6, 75% at B7, 66% at B8, and 50% from B9–B9.5. Stellar data for the individual stars are given in Table 1. Two stars tabulated by Slettebak (1982) and having *IUE* observations, Pleione (HD 23762) and HD 195325, have been excluded from our survey since the heavy line-blanketing by circumstellar material precluded identification or measurement of C IV. We have also excluded stars which are known spectroscopic binaries with primary and secondary stars of different spectral types. This has meant the exclusion of HD 50123 and HD 135734, both of which are tabulated by Slettebak (1982). The *IUE* observations of HD 50123 are discussed by Bjorkman and Snow (1988*b*).

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 December 1. The archival spectra were supplemented by observations from other recent *IUE* observing programs with which we have been associated. More than 100 Be star spectra are included in our survey. Two of the most actively monitored stars account for 30 spectra. Nineteen of the Be stars in our survey had single *IUE* SWP spectra by our cutoff date, although this deficit is being rectified as the result of ongoing *IUE* observing programs. We have selected comparison stars from the compilation of Bruhweiler, Grady,

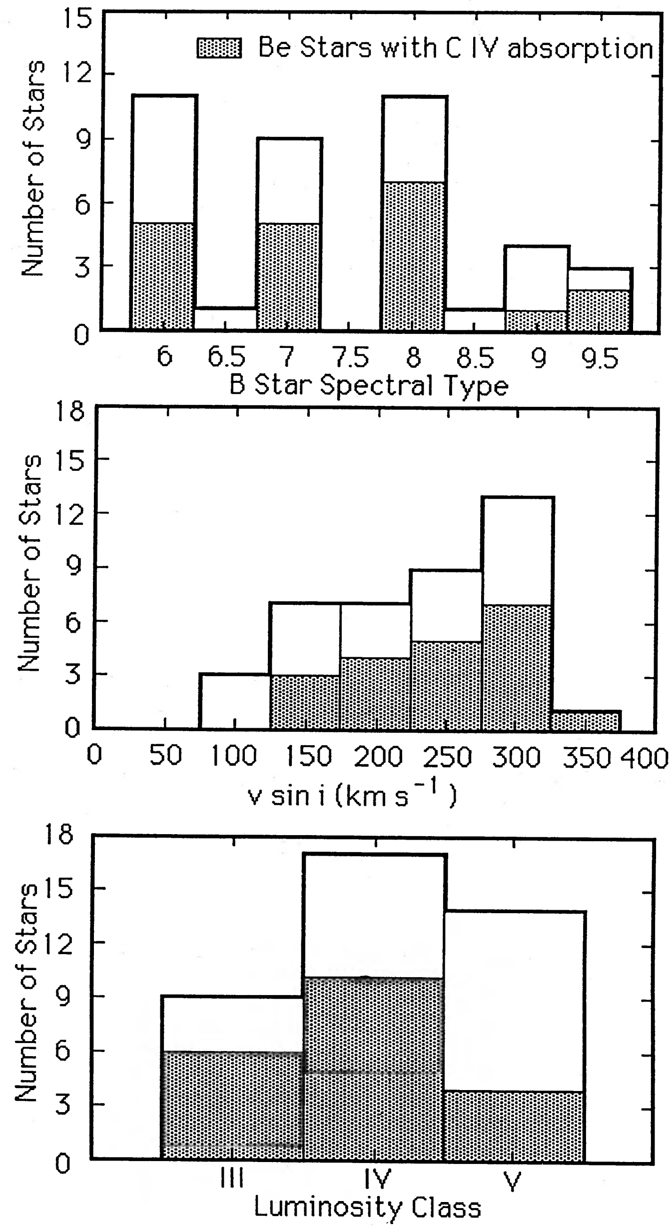

FIG. 1.—Distribution of late-type Be stars as a function of spectral type, luminosity class, and $v \sin i$. The upper panel shows the program Be stars. Shaded portions of the histogram indicate stars with C IV absorption.

and Chiu (1989). These stars were chosen to show no C IV absorption, since Bruhweiler, Grady, and Chiu found that only 20% of their survey of ostensibly normal B8–A1 stars showed C IV absorption. Stellar data for the comparison stars are shown in Table 2.

We have used the same procedure as described in Paper I to reduce the spectra to the form of absolutely calibrated fluxes as a function of wavelength. An archival program such as this one makes use of spectra originally obtained for very different purposes, resulting in a mixture of small-aperture and large-aperture spectra, and in a range of exposure levels. Following Paper I, we have restricted our analysis to relative measurements such as equivalent widths, which can be made on both small-aperture and large-aperture data. In optimally exposed late-type B star spectra, where a peak exposure level of

TABLE 1

PROGRAM B6–B9.5e STARS

HD	STAR NAME	SPECTRAL TYPE[a]	$v \sin i$[b] (km s^{-1})	SWP (mÅ)	$W_{\mathrm{C\,IV}}$[c] (mÅ)	$V_{\mathrm{C\,IV}}$[d]	$W_{\mathrm{Si\,II}}$[c] (mÅ)	C IV Notes	IR EXCESS[e] 12	25	60
210129.........	25 Peg	B6 Ve	150	25955	≤100	...	≤30		...	...	...
22780.........	HR 1113	B6 Ve	280	20846	≤100	...	≤30		...	...	...
26670.........	HR 1305	B6 Ve	280	20435	≤100	...	≤30		...	...	...
183656.........	HR 7415	B6 e–sh	300	17550	940	0	525		...	...	...
45542.........	ν Gem	B6 IVe	170	27663	≤100	...	≤30		0.54	1.35	...
193911.........	25 Vul	B6 IVe	200	28102	580	−190	≤30	var	0.86	1.92	...
110335.........	HR 4823	B6 IVe	250	26124	580	−50	≤100	asym	1.44	2.30	...
23480.........	23 Tau	B6 IVe	280	27666	≤150	0	≤30		0.56[f]	2.72[f]	5.51[f]
23302.........	17 Tau	B6 IIIe	180	27514	≤100	...	≤30		1.22[f]	4.01[f]	...
217675.........	o And	B6 IIIe	260	28842	1210	−90	80	var	...	...	...
138749.........	θ CrB	B6 IIIe	320	14431	1250	−90	≤30	var	−0.50	...	...
6811.........	φ And	B6.5 IIIe	80	10387	≤100	...	sat		0.42	1.17	...
23016.........	13 Tau	B7 Ve	260	27512	370	0	120	asym	...	...	...
21551.........	HR 1051	B7 Ve	300	26895	≤100	...	...		...	...	...
37795.........	α Col	B7 IVe	180	28120	590	−100	≤30		0.83	1.65	2.53
149671.........	η[1] TrA	B7 IVe	230	25958	≤100	...	...		...	...	...
192044.........	20 Vul	B7 IVe	280	28251	490	−128	40	asym	...	...	...
142926.........	4 Her	B7 IVe	300	21151	≤100	...	≤30		...	...	...
209014.........	η PsA	B7 IVe	350	25782	470	−20	≤30	asym	0.67	...	...
23630.........	η Tau	B7 IIIe	140	10378	720	−150	400		0.60	1.42	...
209409.........	o Aqr	B7 IIIe–sh	300	5912	≤100	...	220		0.95	2.07	...
214748.........	ε PsA	B8 Ve	180	26119	≤200	...	≤30		0.53	1.30	...
169033.........	HR 6881	B8 Ve	200	19929	≤100	...	...		...	...	...
58715.........	β CMi	B8 Ve	245	28105	460	−60	50		0.56	1.34	2.23
183914.........	β[2] Cyg	B8 Ve	250	26206	≤100	...	...		...	...	...
224686.........	ε Tuc	B8 IVe	280	26184	780	0	140		...	...	...
185037.........	11 Cyg	B8 Ve	300	26897	350 ± 200	130	≤30		...	...	...
175869.........	64 Ser	B8 IVe	150	14456	350	−150	≤30		...	...	...
47054.........	HR 2418	B8 IVe	260	21909	≤100	...	...		0.80	...	...
29866.........	HR 1500	B8 IVe	305	10047	510	−35	175		0.80	...	...
89080.........	ω Car	B8 IIIe–sh	220	26121	555	0	240	asym	0.67	1.38	2.40
93563.........	HR 4221	B8 IIIe–sh	280	31223	450	0	sat		0.87	1.88	...
144.........	10 Cas	B8.5 IVe	120	20433	≤100	...	sat		...	...	...
100673.........	HR 4460	B9 V(e)	125	15960	≤100	...	...		0.12	...	...
134481.........	κ Lup	B9 Ve	160	21686	≤100	...	...		0.29	0.99	...
24479.........	HR 1204	B9 IVe	100	20434	≤100	...	...		−0.04	...	...
91120.........	HR 4123	B9 IVe	250	27507	650	0	80	asym	...	...	...
212581.........	δ Tuc	B9.5 Ve	200	25783	≤100	...	...		...	...	...
158643.........	51 Oph	B9.5 IVe	220	28113	870	0	sat	asym	3.67	4.82	4.33
166014.........	o Her	B9.5 IIIe	160	20852	590	−100	sat		...	...	...

[a] Spectral types taken, unless noted, from Slettebak 1982. Spectral type for HD 29866 from Hoffleit 1982.

[b] Stellar projected rotational velocities from Slettebak 1982 unless noted. The $v \sin i$ measurement for HD 29866 from Uesugi and Fukuda 1982. The $v \sin i$ measurement for HD 212581 from Slettebak *et al.* 1975.

[c] Equivalent widths specified in mÅ.

[d] Tabulated radial velocities (km s^{-1}) are heliocentric and uncorrected for the stellar radial velocity. These data correspond to the maximum absorption. The C IV absorption maxima are shortward-shifted with respect to the radial velocities tabulated by Wilson 1953, except for HD 183656, HD 23016, and HD 158643.

[e] Infrared color excesses, in magnitudes, measured with *IRAS* taken from Coté and Waters 1987.

[f] Infrared data are contaminated by proximity to the nebulosity in the Pleiades.

200–210 data numbers (DN) is achieved in the vicinity of 1800 Å, the smoothed data at C IV have S/N ratios of 10. Less well-exposed spectra have S/N ratios as low as 5 for data smoothed with five-point running triangular filters. This spectral smoothing, which is essential for the detection of weak spectral features, slightly degrades the velocity resolution to approximately 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}.

TABLE 2

COMPARISON NORMAL B STARS

HD	Star Name	Spectral Type[a]	$v \sin i$ (km s^{-1})	SWP
147152.........	HR 6083	B6 IV	190	19346
87901.........	α Leo	B7 V	280	10379
135382.........	γ TrA	A0 V	175	19355

[a] From Slettebak and Carpenter 1983 and Slettebak *et al.* 1985.

IV. LINE IDENTIFICATION

The major sources of uncertainty in the identification and measurement of C IV absorption in our program stellar spectra are due to uncertainty in continuum placement and line identification.

a) Identification of C IV

As noted by Slettebak and Carpenter (1983) and Hubeny, Harmanec, and Stefl (1986), the region around 1550 Å in B6–B9.5 stars is rich in weak absorption features, predominantly lines of Fe II and Fe III. These lines can be sufficiently strong to mimic the presence of the C IV 1548 Å line, but tend not to show a distinct feature at the position of the C IV 1550.7 Å line, except in stars with very low $v \sin i$. Hubeny, Harmanec, and Stefl (1986) relied upon synthetic spectra for their line identifications. This approach, while valuable for indicating the kinds of problems which can occur in dealing with weak spectral lines in the UV, depends critically upon the accuracy of the available atomic data. Rather than depending upon model spectra, we have chosen to compare our program star spectra with *IUE* spectra of normal B stars of similar spectral type, luminosity class, and $v \sin i$ in order to identify the photospheric absorption features. This technique assumes that, at the signal-to-noise ratio of the *IUE* data, the photospheric spectra of Be stars are indistinguishable from those of normal B stars. This assumption appears to be valid for Be stars (Paper I).

Our normal B comparison stars were chosen from the stars surveyed by Slettebak and Carpenter (1983) which did not have detectable C IV or Si IV absorption features, since a preliminary survey of highly ionized material in B6–A1 stars by Bruhweiler, Grady, and Chiu (1989) indicates that these ions may be present in the UV spectra of only 20% of the apparently normal stars. The comparison stellar data are shown in Table 2.

Graphical comparison of the normal and program star spectra showed that the region near 1522 Å was minimally affected by line blanketing, and could be used as the normalization point for the spectral comparison. The program and comparison star spectra were plotted together, with the comparison star flux normalized to the program star flux at $\lambda 1522$, and portions of the spectrum with significant deviation from the comparison spectrum, approximately 10% or larger in amplitude, were noted. This technique was used to select the range in wavelength for the equivalent width measurement at C IV, and results in the C IV equivalent widths having an uncertainty of approximately 100 mÅ, and upper limits in the case of nondetections of approximately the same amount. This uncertainty is due entirely to uncertainty in the placement of the local continuum and the limited signal-to-noise ratio of the *IUE* spectra. Particularly for the higher $v \sin i$ Be stars, sharp absorption features have a high contrast against the photospheric spectrum and are easily detected. Our identification of C IV absorption tests upon detection of such features in both members of the resonance doublet, at either the transition rest wavelength, or displaced by the same velocity for both features. Figure 2 shows the region from 1530 to 1560 Å in selected program and comparison stars. The rest wavelengths for the C IV resonance doublet are shown by vertical lines.

Late-type Be stars may have additional line blanketing in the vicinity of the C IV resonance lines, due to absorption from the cool circumstellar envelope. Depending upon the velocity characteristics of this material, sharp absorption features may be produced and can present the sort of difficulties in line identification discussed by Hubeny, Harmanec, and Stefl (1986). Some of our program stars have spectra which are affected by such line blanketing. Our estimates of the amount of C IV present in these spectra are therefore correspondingly more uncertain.

Our program star spectra can be divided into three groups: those with minimal line blanketing from 1520 to 1570 Å, those with moderate line blanketing, and those which are substantially veiled. The spectra with minimal line blanketing have $f_{\lambda=1552} = f_{\lambda=1542}$ and $f_{\lambda=1560}$ only slightly lower. The spectrum outside the 1547–1551 Å region forms a flat continuum, particularly in the higher $v \sin i$ stars. This flat continuum is used as the continuum level for our C IV measurements. The program star spectra shown in Figure 2 exhibiting this kind of spectrum are θ CrB, HD 37795, HD 29866, HD 91120, and HD 224686. C IV in these spectra, if present, is typically visible as a strong absorption feature in both members of the resonance doublet, with maximum absorption strength typically 50% of the continuum flux, and thus at least a 3 σ detection, even allowing for linearity errors in the *IUE* data. Moderately line-blanketed spectra differ from the optimal spectra described above by showing a number of absorption features in the 1520–1570 Å region such that the spectrum does not form a flat pseudocontinuum. The signatures of such blanketing are apparent emission features in the vicinity of C IV, which have maximum fluxes less that the continuum flux at 1522 Å. In these stars $f_{\lambda=1560} \leq f_{\lambda=1542} \leq f_{\lambda=1522}$. Spectra with this characteristic in Figure 2 are HD 158643 and HD 166014. The early spectra of o And described by Hubeny, Harmanec, and Stefl (1986) also fall into this category. Depending upon the intrinsic strength of any C IV absorption, detection may be difficult. Heavily veiled spectra make identification of C IV absorption even more challenging. In this case the $f_{\lambda=1560}$ absorption is nearly saturated, and the remaining spectrum tends to be rather chopped up. HD 23630 in Figure 2 is one such example.

b) Si II *Shell Absorption Features*

A characteristic feature of the spectra of many late-type Be stars is the presence of absorption features superposed on the Balmer lines of hydrogen, and also sometimes seen in the lines of singly ionized metals such as Fe II. These features, termed "shell" absorption features, which are quite sharp and comparatively undisplaced from the transition rest wavelength, are more common in the cooler Be stars than in the hotter stars. Similar features have been reported (Oegerle and Polidan 1984) in the UV spectra of Be stars and are particularly easily detected in the ground-state and excited-state transitions of singly ionized species such as Si II. The *IUE* SWP high-dispersion spectrum contains a number of Si II transitions, including UV multiplet 2 of Si II. The lines of this multiplet are located at 1526.71 and 1533.43 Å and are sufficiently close in wavelength to the C IV resonance doublet to permit us to analyze them as part of our C IV survey. The utility of these Si II lines is that while the 1526.71 Å transition can be produced in low-density environments, such as the interstellar medium, the 1533.43 Å transition can only be produced in higher density regions, such as a circumstellar envelope, or star formation regions such as Orion. None of our program stars are sufficiently heavily reddened for the Si II $\lambda 1533$ feature to be produced in the interstellar medium. Since the majority of our program stars have large values of $v \sin i$, and consequently exhibit broad photospheric absorption features, sharp absorption cores have a high contrast against the photospheric spectrum and are easily detected. Thus the Si II lines, particularly $\lambda 1533$, are useful indicators of circumstellar shell absorption in our survey stars, especially when compared with our standard stars.

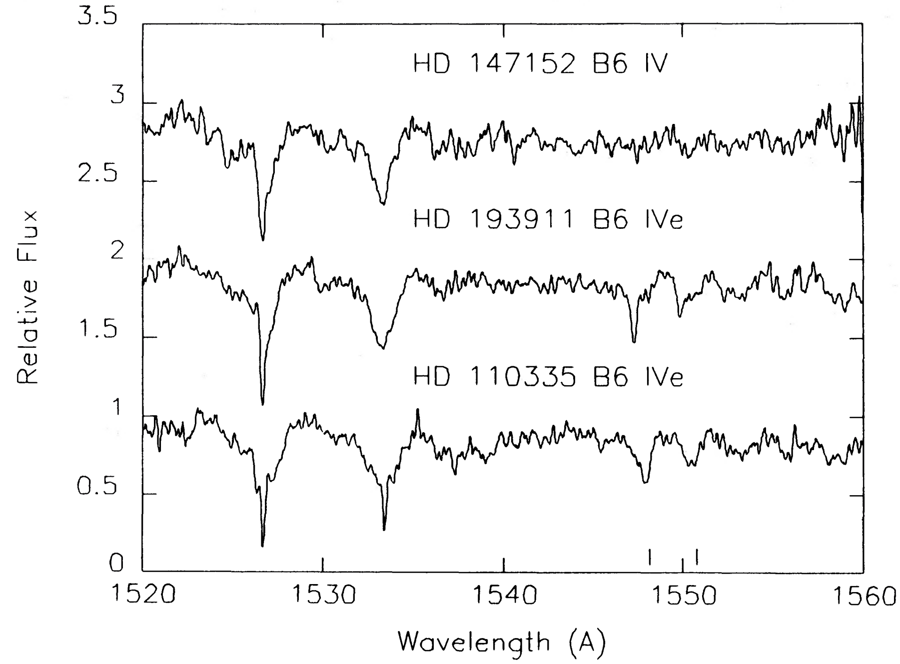

FIG. 2*a*

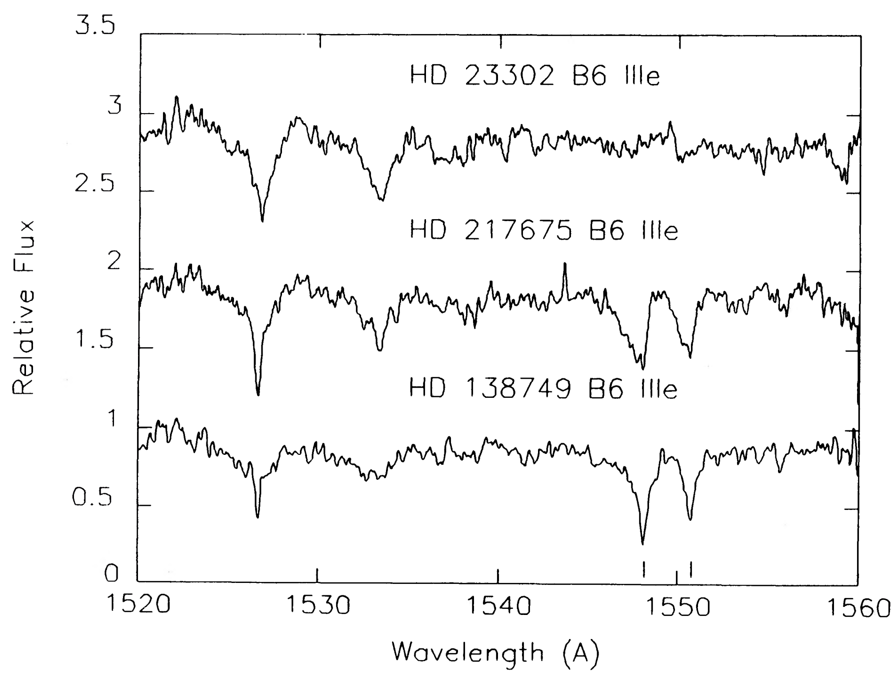

FIG. 2*b*

FIG. 2.—*IUE* high-dispersion spectra of selected program and comparison stars from 1520 to 1560 Å. Vertical marks at the bottom of each panel indicate the rest wavelengths of the C IV resonance doublet. (*a*) C IV and Si II shell absorption at B6 IV. The comparison star HD 147152 is shown above HD 193911 and HD 110335. Note the Si II shell absorption in the spectrum of HD 110335, which is not present in the other two stars. (*b*) C IV absorption at B6 III. C IV absorption is strongly present in HD 217675, which exhibits strongly asymmetric C IV profiles, and in HD 138749, but not in HD 23302. (*c*) C IV and Si II shell absorption at B7. The comparison star HD 87901 is shown above HD 23016 and HD 37795, both of which exhibit C IV absorption. Si II shell absorption is also seen in HD 23016. (*d*) C IV and Si II absorption at B7 (*continued*). HD 192044 shows weak Si II shell absorption in addition to C IV. HD 209014 has slightly asymmetric C IV profiles. HD 23630 shows strong absorption at the position of the C IV resonance doublet. The Fe II absorption feature at 1560 Å, which is saturated, indicates that some of the absorption in the vicinity of C IV is likely to be due to iron. (*e*) C IV and Si II absorption at B8. All three Be stars show weak C IV absorption. (*f*) C IV and Si II shell absorption at B8 and B9. Strong C IV absorption is present in HD 29866, HD 224686, and HD 91120. These stars also show strong Si II shell absorption features at 1533.4 Å. (*g*) C IV and Si II shell absorption at B9. HD 158643 and HD 166014 show strong C IV absorption. These stars also have strong Si II absorption features, but it is not possible to distinguish shell absorption from the photospheric profile in these stars. The normal star HD 135382 is shown for comparison.

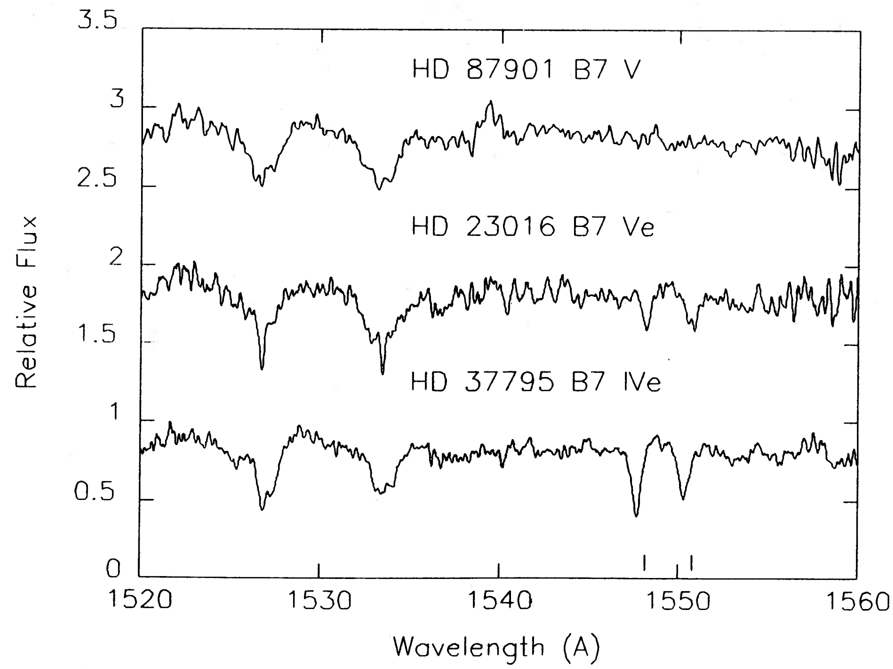

FIG. 2c

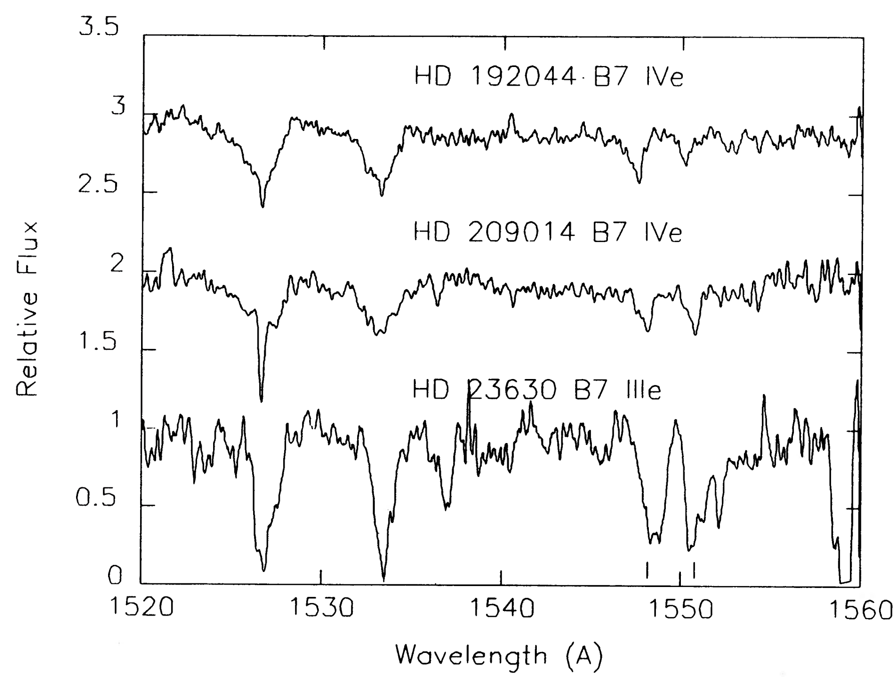

FIG. 2d

V. RESULTS

Following Paper I we will describe the individual stars showing either C IV absorption or circumstellar Si II, and then discuss the results of our survey as a whole. Figure 2 shows the region from 1520 to 1560 Å, including both the Si II UV multiplet 2 transitions and the C IV resonance transition for selected Be stars in our sample.

a) *Individual Stars Showing Wind or* Si II *Shell Absorption*

HD 183656 (*HR 7415, V923 Aql, B6e-sh, v* sin *i = 300* km s^{-1}).—Slettebak and Carpenter (1983) included this star in their survey of winds in late-type B stars. Strong shell absorption is present in the one well-exposed spectrum, SWP 17550, with Si II λ1533 close to saturation. Other lines are also strongly in absorption when compared to either a B6 Ve or B6 IVe

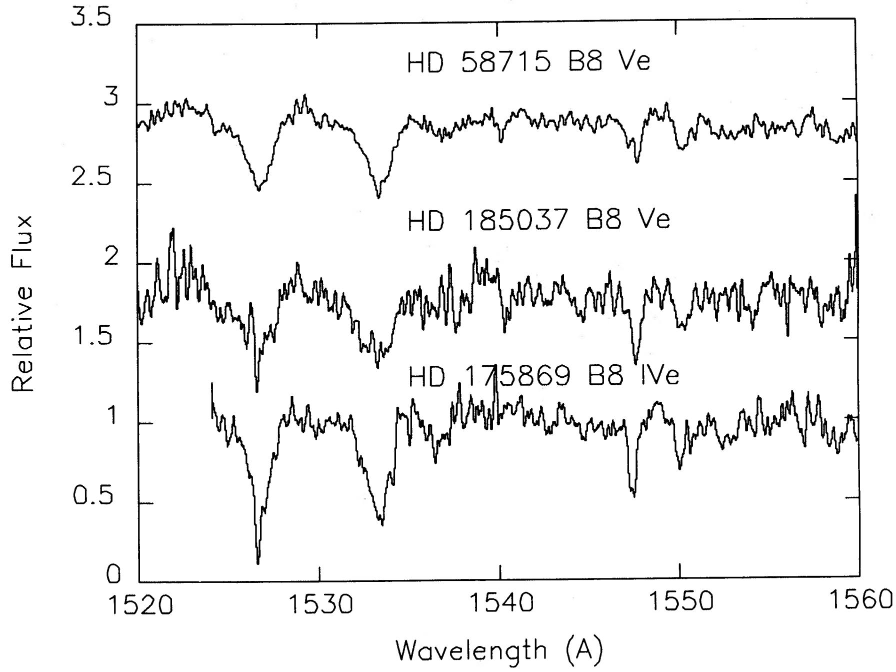

FIG. 2*e*

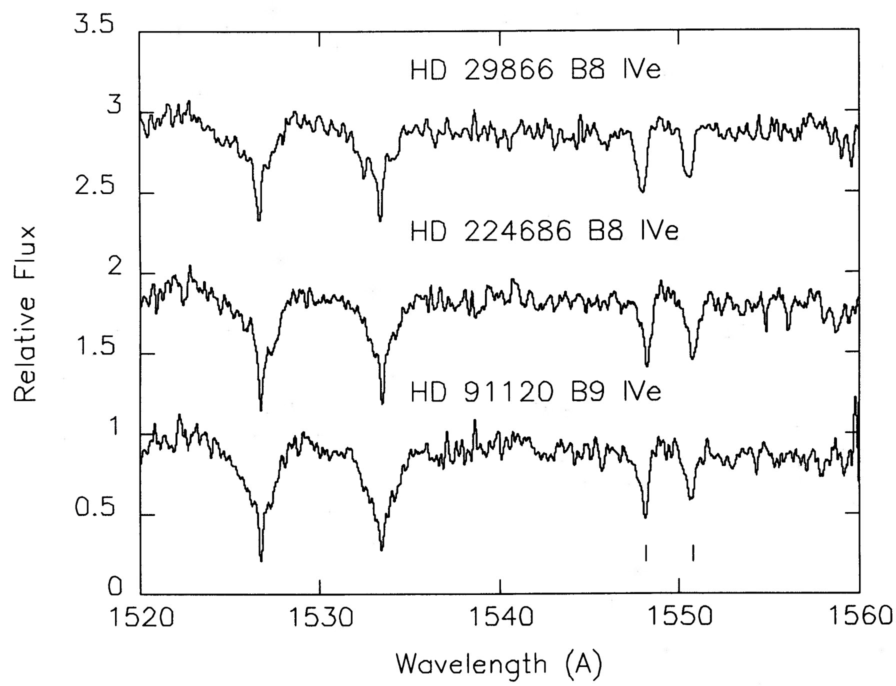

FIG. 2*f*

comparison star. Identification of C IV in this star's spectrum is complicated by the other absorption lines in the vicinity. An upper limit to the C IV absorption of 0.9 Å is obtained by assuming that all of the absorption from 1546.38 to 1550.8 Å is due to C IV. In view of the heavy line blanketing of the spectrum, this almost certainly overestimates the true C IV absorption. Ballereau *et al.* (1987) present double Hα profiles from 1976 which are centrally reversed. Slettebak (1982) also reports double emission in Hα for this star.

HD 193911 (*HR 7789, 25 Vul, B6 IVe, v* sin *i* = *200* km s^{-1}).—The two SWP spectra of this star correspond to a detection and an upper limit for wind absorption. No detectable shell absorption in Si II λ1533 is seen in either of the *IUE* spectra when compared with HD 147152 (B6 IV). Barker (1984) reports a narrow Hα emission peak with intensity 2.3 times the continuum from his 1982–1983 data. Andrillat (1983) shows a double Hα profile from 1981. Waters, Coté, and Lamers (1987) estimate an uncertain infrared mass loss rate of $10^{-8.7}$ $M_\odot$ yr^{-1}.

HD 110335 (*HR 4823, B6 IVe, v* sin *i* = *250* km s^{-1}).—C IV

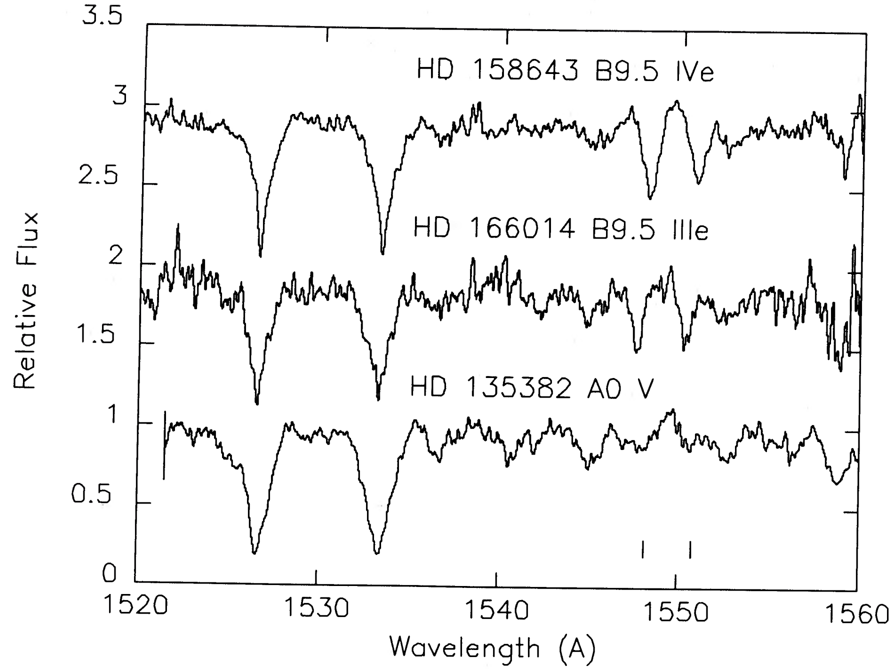

FIG. 2*g*

absorption is present in this star. An upper limit, which probably includes some contribution from other blended absorption lines, most likely Fe II and Fe III, in the vicinity is 0.57 ± 0.1 Å. Slettebak (1982) reported a double emission profile from this star. Waters, Coté, and Lamers (1987) find an infrared mass loss rate for this star of $10^{-8.5}$ $M_{\odot}$ yr^{-1}.

HD 217675 (*HR 8762, o And, B6 IIIe, v* sin *i* = *260* km s^{-1}).—Omicron And developed optical shell absorption features in 1980 (Bossi *et al.* 1982) which were still present in 1981 and 1982 (Baade *et al.* 1982). This shell episode was accompanied by a significant increase in the B-band linear polarization (Hayes 1982) over that measured in 1978–1979. Barker (1984) reports that Hα was in absorption in 1980. Shell absorption features were developing and reaching a maximum absorption depth of 0.5 times the continuum by 1983. Hα showed weak *V* and *R* emission peaks at this time. Slettebak (1982) reported double emission in Hα. Hubeny, Harmanec, and Stefl (1986) have discussed some early UV spectra of this star. The early *IUE* spectra obtained in 1978 and early 1979, SWP 2393 and SWP 3896, were obtained using the small aperture. These spectra, shown in Figure 4*b*, show a sharp absorption core in Si II λ1533 which was strong in the 1978 spectrum, and weaker, although still present in the 1979 spectrum. Some C IV is possibly present in both of these spectra, although the substantial line blanketing, as noted by Hubeny, Harmanec, and Stefl (1986), makes this identification quite uncertain. The maximum line blanketing observed in the *IUE* spectra occurred at the time of the 1981 August 18 observation, where the depressed fluxes in the vicinity of 1560 indicate the presence of Fe II absorption. No *IUE* spectra were obtained from the end of 1981 until 1986 June, when minimal shell absorption was present in Si II, the other line blanketing was at most modest, and unambiguous C IV absorption, characterized by a blue asymmetric profile was present. Additional spectra obtained in 1986 show strong and variable C IV absorption extending 400 or more km s^{-1} from the transition rest wavelength. As shown in Figure 4*b*, the 1986 data were obtained at a time of minimal circumstellar shell absorption in the Si II lines. The C IV profiles and temporable variations in the spectra of this star are reminiscent of some earlier type Be stars including P Car (Paper I).

HD 138749 (*HR 5778, θ Cr B, B6 IIIe, v* sin *i* = *320* km s^{-1}).—This star is one of the best studied Be stars in both the optical and UV portions of the spectrum. During the time period of the *IUE* monitoring of this star, the optical spectrum has shown absorption in Hα (Andrillat and Fehrenbach 1982; Barker 1984; Doazan *et al.* 1986*a*). Results of the long-term *IUE* studies of the stellar wind in this object have been presented by Carpenter, Slettebak, and Sonneborn (1984), Doazan *et al.* (1984), Underhill (1985), and Doazan *et al.* (1986*a*, *b*). One of the most interesting results of these studies has been the detection of a stellar wind at times when Hα shows only photospheric absorption, and evidence that the strength of the C IV absorption is not, in general, correlated with the strength of the Hα emission. The *IUE* spectra show C IV absorption strengths ranging from equivalent widths of 1.25 Å down to upper limits of 120 mÅ. In the strong wind absorption spectra the centroid of the C IV absorption is frequently shortward-shifted with respect to the line rest wavelength. Comparison of the Si II profiles with the comparison stars, and with the other B6 IIIe stars in our sample, shows that both lines of Si II (2) at λλ1526.7, 1533.43 show less absorption than is expected based on the stellar *v* sin *i*, spectral type, and luminosity class. This may indicate the presence of some emission in these lines.

HD 23016 (*HR 1126, 13 Tau, B7 Ve, v* sin *i* = *260* km s^{-1}).—Weak shell absorption is present in Si II 1533 Å when compared with α Leo, contributing 120 ± 30 mÅ. Si II λ1526 is unsaturated and is very likely circumstellar in origin. Some C IV appears to be present, although weak, in this star. Significant line blanketing due to other species also is present, making the 370 ± 200 mÅ detection uncertain. Barker (1984) found Hα emission 1.3 times the continuum flux, with a central reversal, and possible flanking photospheric absorption. Slettebak (1982) also reported double emission in Hα.

HD 37795 (*HR 1956, α Col, B7 IVe, v* sin *i* = *180* km

s^{-1}).—C IV absorption is unambiguously present in this star given the weakness of the adjacent line absorption. The centroid of the C IV absorption is displaced to short wavelengths by approximately 100 km s^{-1}. No absorption is present at the rest wavelength. This star shows no detectable shell absorption when compared with α Leo. Dachs *et al.* (1986) report single emission at Hα, but double emission in Hβ. Higher resolution Hα data, obtained in 1982, show a double emission structure, but with only a small separation in radial velocity between the emission peaks (Hanuschik, Kozok, and Kaiser 1988). CTIO spectra obtained in 1984 September show a single broad emission peak at Hα with no obvious reversal, overlying a broad photospheric absorption profile. Hβ shows a double-peaked profile inside a broad photospheric absorption profile. Hγ shows $V/R > 1$ with the same general structure as Hβ, only with narrower emission peaks. He I absorption is weak, if present. Hanuschik (1987) obtained Hα and Fe II emission profiles showing double profiles in 1985 January. Waters, Coté, and Lamers (1987) estimate an infrared mass-loss rate for this star of $10^{-8.8}$ $M_\odot$ yr^{-1}.

HD 192044 (*HR 7719, 20 Vul, B7 IVe, v* sin *i* = *280* km s^{-1}).—Weak C IV absorption is present with a detection at 490 ± 100 mÅ. This star shows no detectable shell absorption at Si II λ1533 when compared with α Leo. Barker (1984) reported Hα emission 2.3 times the continuum, with possible very weak central absorption. Andrillat (1983) reported double emission in Hα.

HD 142926 (*HR 5938, 4 Her, B7 IVe–sh, v* sin *i* = *300* km s^{-1}).—This star shows weak shell absorption at Si II λ1533.4, as well as other spectral lines. At least some of the unsaturated Si II λ1526.7 absorption may be circumstellar. The shell contributes 130 ± 40 mÅ at 1533.4 Å. Barker (1984) reported Hα emission 1.2 times the continuum in 1980–1981 and declining through 1983 with an increasingly strong central absorption. Andrillat and Fehrenbach (1982) reported double Hα emission with possible central reversal in 1980.

HD 209409 (*HR 8402, o Aqr, B7 IVe, v* sin *i* = *305* km s^{-1}).—This star shows weak shell absorption at Si II λ1533. Similar absorption is present in Si II λ1526.7, indicating a circumstellar origin for that feature rather than an interstellar origin. At 1533.4 Å, the shell contributes 220 ± 40 mÅ. Barker (1984) reported Hα emission 2.8 times the continuum, with a strong central absorption and minor V/R variations. Andrillat (1983) reported double Hα emission with a strong central reversal in 1981 data. CTIO 1.5 m observations made in 1983 August showed broad double-peaked emission at Hα and Hβ. Hγ and Hδ showed sharp absorption cores. He I λλ4921, 5018 showed sharp absorption cores. The He I λ6678 line was filled in. Andrillat, Jaschek, and Jaschek (1988) noted shell absorption cores in the Paschen lines of hydrogen, as well as near-infrared emission from Fe II, O I, and possibly Ca II in data obtained from mid-1982 through mid-1983. Waters, Coté, and Lamers (1987) derive an infrared mass loss rate for this star of $10^{-8.8}$ $M_\odot$ yr^{-1}.

HD 209014 (*HR 8386, η PsA, B7 IVe, v* sin *i* = *350* km s^{-1}).—Weak C IV absorption is present in SWP 25782, with an absorption equivalent width of 470 ± 100 mÅ. No Si II shell absorption is seen. Slettebak (1982) reported double Hα emission in this star. CTIO 1.5 m observations from 1983 August reveal an unusual Hα profile with sharp double-peaked emission superposed on a very broad underlying *emission* profile. The sharp emission peaks are separated by 200–250 km s^{-1}. Hβ shows only two sharp emission peaks within a broad photospheric absorption profile. CTIO data obtained on 1984 September 11/12 showed a "boxlike" Hα profile, with double emission peaks. Hβ showed a similar profile superposed on a very broad photospheric absorption profile. No striking He I (λλ5018 or 6678) absorption was present.

HD 23630 (*HR 1165, η Tau, B7 III, v* sin *i* = *140* km s^{-1}).—This star has a long history of optical observations. Andrillat and Fehrenbach (1982) reported double and broad Hα emission. Hanuschik, Kozok, and Kaiser (1988) observed a double Hα emission profile with only a small radial velocity separation between the emission peaks in 1982 observations. Barker (1983), using lower resolution, observed only a single blended emission profile. Slettebak (1986) observed a double emission profile in 1984 November. The UV spectrum of this star has been studied by Slettebak and Carpenter (1983). Some C IV seems likely to be present, although the exact amount is uncertain given the strong absorption from the other species. An upper limit to the C IV is 720 ± 100 mÅ, although the strength of other absorption features from 1550 to 1560 Å suggests that this is an overestimate of the true C IV absorption. This star shows a strong absorption core at Si II λ1533, which we interpret as being formed in the circumstellar shell, based on the presence of additional line blanketing in the UV spectrum.

HD 58715 (*HR 2845, β CMi, B8 Ve, v* sin *i* = *245* km s^{-1}).—β CMi has been regularly monitored in the optical during the 1980s. Barker (1984) reports a rather narrow emission feature at Hα, with intensity 1.7 times the continuum, having a weak central absorption, and minor V/R variations. The emission was flanked by photospheric absorption. Andrillat and Fehrenbach (1982) reported double Hα emission. Slettebak (1986) observed a double emission profile in 1984 November similar to that seen by Barker (1984). *IRAS* observations of this star have been analyzed by Waters, Coté, and Lamers (1987), who derive an infrared mass-loss rate of 10^{-9} $M_\odot$ yr^{-1}. No sharp Si II absorption core is detectable in the *IUE* data. Weak C IV absorption of 460 ± 100 mÅ is present.

HD 185037 (*HR 7457, 11 Cyg, B8 Ve, v* sin *i* = *300* km s^{-1}).—This star shows weak C IV absorption at 350 ± 200 mÅ in its single and rather noisy *IUE* spectrum. Barker (1984) reported Hα emission 1.6 times the continuum, with possible central reversal and flanking photospheric absorption. Andrillat (1983) presents a double Hα profile from 1981.

HD 175869 (*HR 7158, 64 Ser, B8 IVe, v* sin *i* = *150* km s^{-1}).—This star shows variable C IV absorption in three of the higher signal-to-noise ratio *IUE* spectra. C IV equivalent widths range from 390 ± 100 mÅ, down to 100 mÅ. Barker (1984) found only broad photospheric Hα absorption with a weak and indistinct central emission peak in this star. Slettebak (1982) reported weak Hα emission in this star. 1983 August observations made at the CTIO 1.5 m telescope showed weak double-peaked broad emission on the hydrogen lines, with a possible absorption component. The detection of some circumstellar shell absorption is confirmed by the presence of a weak Si II λ1533.4 absorption core.

HD 29866 (*HR 1500, B8 IVe, v* sin *i* = *305* km s^{-1}).—C IV is detected in this star with absorption of 510 ± 100 mÅ against a comparatively featureless continuum. This star shows a weak sharp absorption feature ($W_\lambda \approx 100$ mÅ) in Si II λ1533.4. Andrillat (1983) reported double Hα emission with $V > R$ in 1981 data.

HD 224686 (*HR 9076, ε Tuc, B8 IVe, v* sin *i* = *220* km s^{-1}).—With the exception of the C IV resonance lines and the Si II multiplet 2 lines, the UV spectrum of this star from 1520 to 1570 Å is identical to that of δ Tuc. At Si II λ1533.4, this star shows a sharp absorption feature superposed on the broad photospheric absorption typical of B8–B9. The shell component contributes 137 ± 30 mÅ. The C IV profile in this star is comparatively strong for the spectral type at 560 ± 100 mÅ. Hanuschik, Kozok, and Kaiser (1988) observed double and weak Hα emission in 1982, as did Dachs *et al.* (1986). CTIO 1.5 m observations in 1983 August showed a broad central reversal on the hydrogen lines. CTIO observations from 1984 September show Hα with weak, but widely separated, double emission peaks. Emission was very weak or absent at Hβ.

HD 91120 (*HR 4123, B9 IVe, v* sin *i = 250* km s^{-1}).—C IV absorption in this star was first identified by Molaro *et al.* (1985) and is quite strong given the late spectral type (650 ± 100 mÅ). Weak shell absorption is detectable in Si II λ1533.4. Si II λ1526.7 is unsaturated, and a circumstellar origin for much of this absorption feature cannot be ruled out. Barker (1984) found narrow Hα emission with intensity 1.3 times the continuum having moderate central absorption and flanked by weak photospheric absorption. Andrillat and Fehrenbach (1982) reported double Hα emission in this star.

HD 158643 (*HR 6519, 51 Oph, B9 IVe, v* sin *i = 220* km s^{-1}).—C IV in this star is quite strong, 870 ± 100 mÅ, given the late spectral type. This star shows strong, and essentially saturated, Si II λ1533.4 absorption, although the strength of the Si II absorption is less than is observed in the A0 V comparison star. Slettebak (1982) found double Hα emission in this star. 1983 August CTIO 1.5 m telescope observations showed a strong central reversal in the Hα profile from this star. In 1984 September data from CTIO showed possible sharp emission superposed on a broader double Hα emission profile. The Hβ profile was in the form of weak double emission superposed on a broad photospheric absorption profile.

HD 166014 (*HR 6779, o Her, B9.5 IIIe, v* sin *i = 160* km s^{-1}).—Some C IV is detected in this star. The total equivalent width of 590 ± 100 mÅ represents an upper limit, since enhanced line absorption due to Fe II is present from 1540 to 1555 Å. Strong Si II λ1533.4 absorption is present. Slettebak (1982) reported weak and possibly double Hα emission. Barker's (1984) data showed photospheric Hα absorption with a central sharp emission peak, which was centrally reversed.

b) The v sin *i Threshold for* C IV *Detections*

Twenty out of our 40 Be stars, or 50%, show C IV absorption in one or more *IUE* spectra. This detection percentage is comparable to that found by previous studies of earlier Be stars, which contained similar numbers of both stars and spectra (Henrichs 1984), and suggests that the frequency of detection of highly ionized material around Be stars does not depend strongly upon stellar effective temperature.

Eleven of the program Be stars (HD 110335, HD 193911, HD 217675, HD 138749, HD 37795, HD 192044, HD 175869, HD 23630, HD 58715, HD 29866, and HD 166014), or 55% of those with C IV absorption, show shortward-shifted C IV absorption features in one or more *IUE* spectra. In seven of these stars the C IV absorption is in the form of one approximately Gaussian feature, similar to the shortward-shifted discrete components typical of the B0.5–B5e stars (Paper I). In the majority of these stars, little or no absorption is detectable at the line rest wavelength, again reminiscent of early-type Be stars such as 66 Oph (Grady *et al.* 1987). These results strongly suggest that the C IV absorption in these stars is produced by the same mechanism as in the hotter and more luminous B0.5–B5e stars. The presence of significant C IV profile variations in several of the program stars (Figs. 4*a* and 4*b*) further suggests that the C IV is produced in a stellar wind and is incompatible with the suggestion of Molaro *et al.* (1985, 1986) that the C IV absorption in these stars is produced in the local interstellar medium.

Figure 3*a* shows C IV equivalent widths as a function of

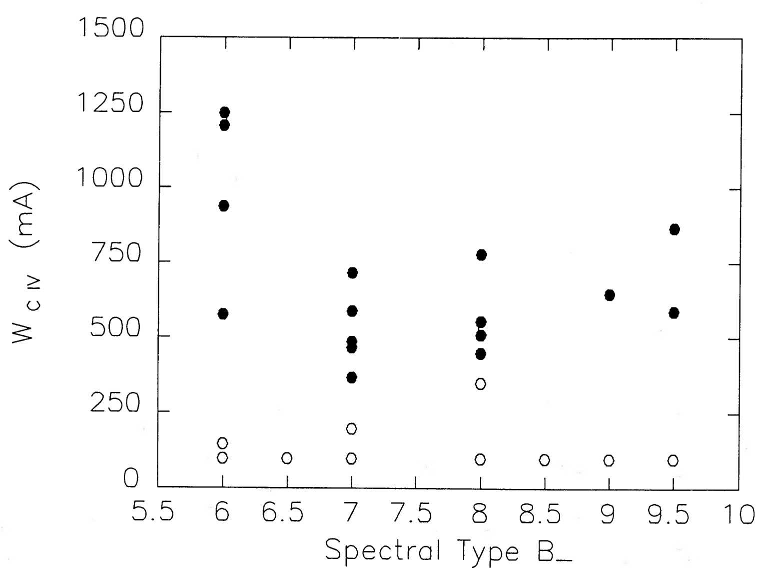

FIG. 3*a*

FIG. 3.—The v sin i threshold for highly ionized stellar winds, the presence of Si II shell absorption, and *IRAS* 12 μm color excesses. (*a*) C IV equivalent widths as a function of stellar spectral type. The solid circles indicate the stars with v sin $i \geq 140$ km s^{-1}. The open circles are the stars with lower values of v sin i. (*b*) Distribution of C IV detections as a function of both spectral type and v sin i. The upper panel shows the detections (*filled symbols*) for all spectral types. The middle panel shows luminosity class V. No C IV is seen for the stars with v sin $i \leq 200$ km s^{-1}. The bottom panel shows the C IV detections in the luminosity class IV and III stars. Here no C IV is found for stars with v sin $i \leq 140$ km s^{-1}. (*c*) Distribution of Si II shell absorption features as a function of stellar v sin i. (*d*) Distribution of *IRAS* 12 μm color excesses for the program Be stars. The data are taken from Coté and Waters (1987).

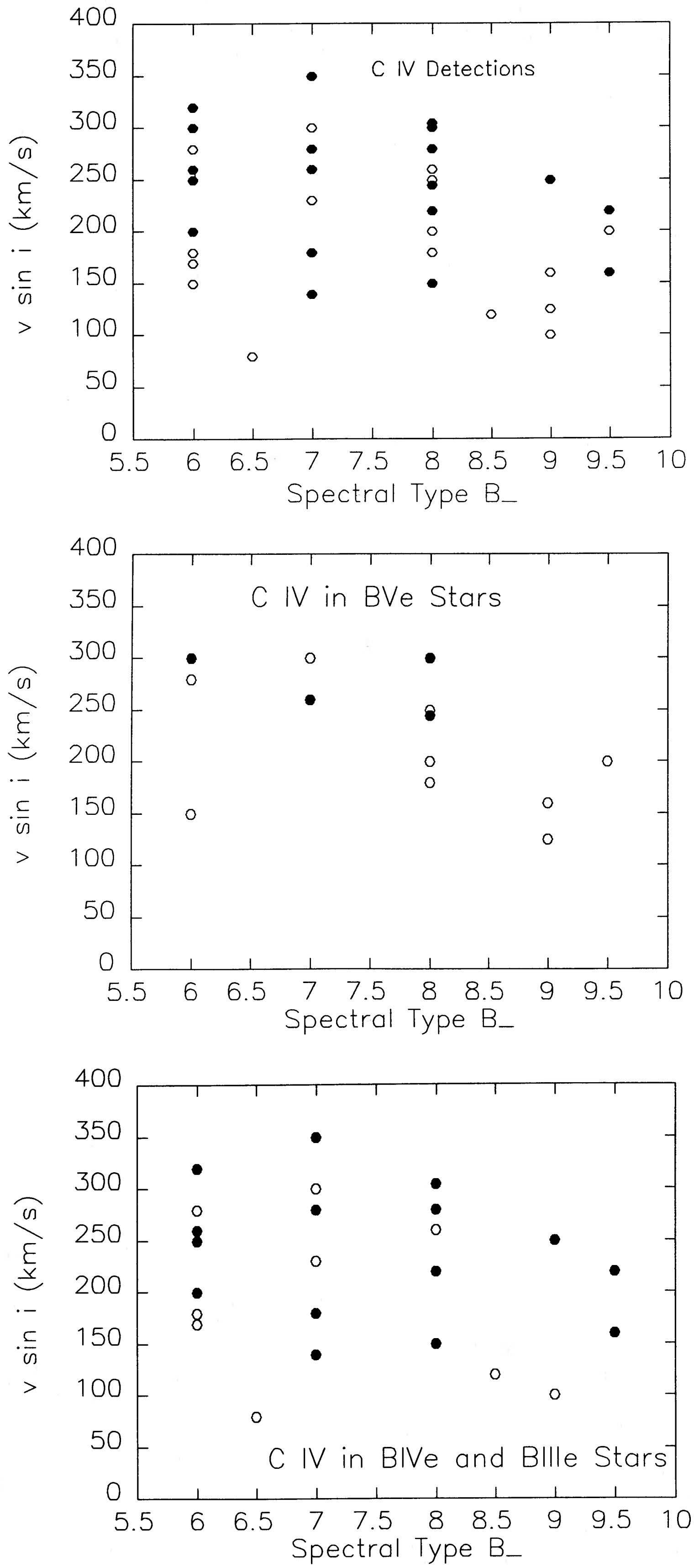
C IV Detections
v sin i (km/s)
Spectral Type B_
C IV in BVe Stars
v sin i (km/s)
Spectral Type B_
C IV in BIVe and BIIIe Stars
v sin i (km/s)
Spectral Type B_

FIG. 3*b*

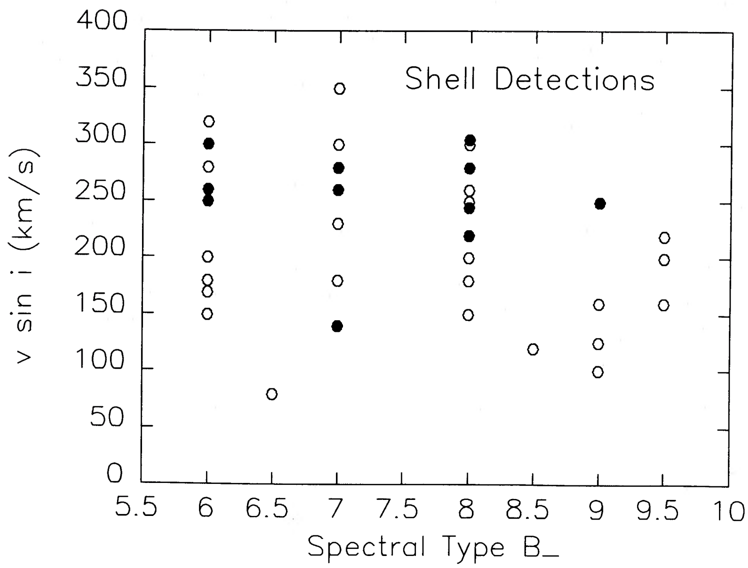

FIG. 3c

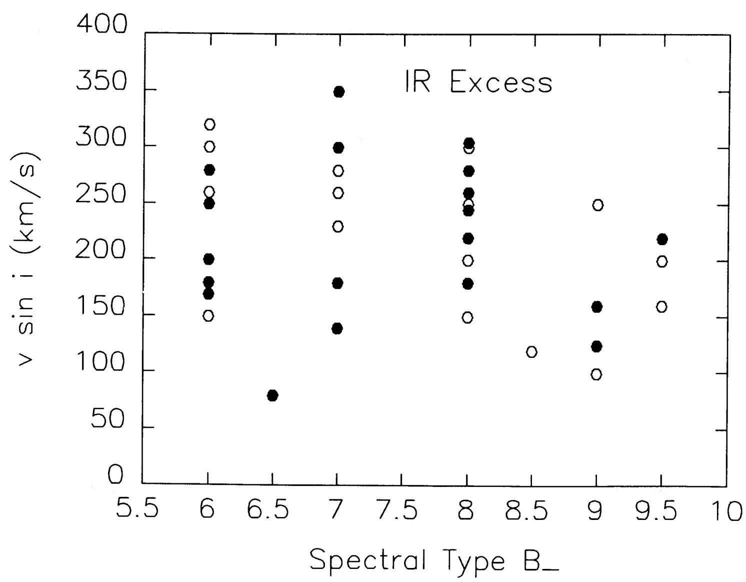

FIG. 3d

spectral type. Figure 3b shows the distribution of equivalent widths as a function of both spectral type and $v \sin i$. We detect C IV absorption in the luminosity class V stars only for stars with $v \sin i > 200$ km s^{-1}. The threshold for detection for luminosity class IV and III is lower and is approximately 140–160 km s^{-1}. The higher threshold for detection of C IV in luminosity class V stars does not seem to be an artifact of the frequency of observation by *IUE*, since many of the luminosity class IV and III stars in the same $v \sin i$ range have the same number of observations. We note however, in view of the variability of the stellar winds in Be stars, and the comparative incompleteness of the data set, that the apparent dependence of $v \sin i$ threshold on luminosity class may vanish as additional UV spectra of these stars are acquired.

c) Si II *Shell Absorption*

Fourteen of the program stars, or 36%, show sharp absorption cores in the 1533.4 Å line of Si II. In five of these stars, HD 6811, HD 93563, HD 144, HD 158643, and HD 166014, the absorption is essentially saturated and cannot be easily distinguished from the photospheric absorption profile. In the remaining nine stars, the absorption core is distinctly sharper than the photospheric profile. The majority of these stars have previously been identified as having sharp absorption cores in the Balmer lines of hydrogen, or in optical lines of Fe II (Briot, 1986), implying that the Si II absorption cores are produced in the immediate circumstellar environment of these stars. In all cases the absorption is centered at the transition rest wavelength.

We find a threshold in $v \sin i$ for the detection of unsaturated circumstellar Si II absorption (Fig. 3c). Shell features are observed below $v \sin i = 200$ km s^{-1} only for one luminosity class III star, HD 23630. All of the remaining detections occur in stars with $v \sin i \geq 200$ km s^{-1}. This threshold is consistent with the $v \sin i$ threshold observed in C IV.

While similar $v \sin i$ thresholds occur in both the C IV and

Si II data sets, our data do not suggest a direct correlation between the strength of C IV absorption and the detection of circumstellar Si II. Only 23% of the program stars have Si II absorption cores which are unambiguously circumstellar, whereas 50% of the program stars have C IV absorption. Only 39% of the program star spectra showing C IV absorption also have Si II shell features. Two of the program stars without detectable C IV absorption have distinct Si II shell features. Temporal variations in the highly ionized stellar wind, and circumstellar shell may account for the lack of a detailed correlation. Grady, Bjorkman, and Snow (1987) found that B0.5–B5e stars with shell features and C IV absorption tended to have weaker C IV absorption than other Be stars of the same spectral type and $v \sin i$. The only star in our sample with observations made during and well after a shell episode is *o* And. As shown in Figure 4*b*, the early spectra obtained from 1978 to 1981, particularly the spectrum obtained on 1981 day 320, show apparently weaker C IV absorption and greater line blanketing in adjacent parts of the spectrum than in the 1986 spectra, by which time the shell had dissipated. This suggests that the effect noted by Grady, Bjorkman, and Snow (1987) may well extend to later spectral types, but additional observations of objects during and following shell episodes will be needed to confirm this result.

VI. COMPARISON WITH OTHER DATA SETS

a) *Infrared*

Waters (1986) found a threshold in $v \sin i$ for the detection of *IRAS* 12 μm color excesses in Be stars at approximately 200 km s^{-1} for stars later than approximately B4e. Stars with $v \sin i$ smaller than 200 km s^{-1} showed little or no 12 μm color excess, whereas stars with higher values of $v \sin i$ showed a range of color excesses, as might be expected from the dramatic variability in the outer atmospheres of Be stars. Waters's (1986) threshold is consistent with the $v \sin i$ threshold we observe in C IV. *IRAS* 12 μm color excess data taken from Coté and Waters (1987) are shown in Figure 3*d*. With the exception of HD 6811, the infrared data are consistent with a $v \sin i$ threshold in the vicinity of 150 km s^{-1} for luminosity classes V–III. No direct correlation between *IRAS* color excesses and C IV or Si II equivalent widths is seen, although Bjorkman and Snow (1988*a*) did find that those Be stars with *IRAS* excess fluxes tended to show larger C IV and Si IV equivalent widths than those without *IRAS* excess fluxes. In fact, they found evidence for distinct differences in the mean C IV equivalent widths between *IRAS* Be stars, non-*IRAS* Be stars, and normal B stars.

The absence of a direct correlation may be explained by the

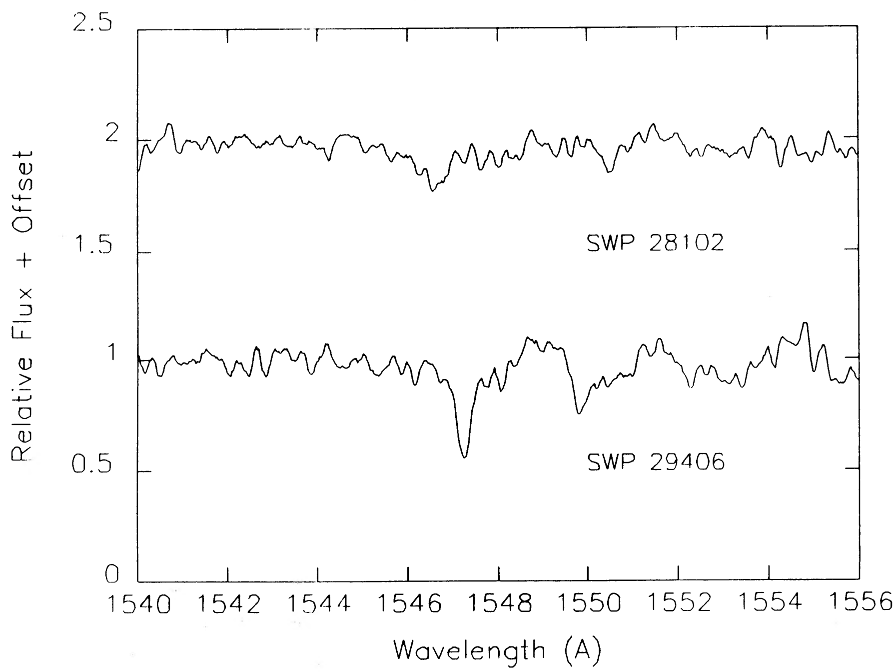

FIG. 4*a*

FIG. 4.—Wind variability in B6e stars. (*a*) C IV variability in HD 193911 (B6 IVe). The available *IUE* high-dispersion spectra of HD 193911 include both a weak wind spectrum (SWP 28102), and a strong wind spectrum (SWP 29406). The C IV absorption in the strong wind spectrum is clearly shortward-shifted with respect to the rest wavelength. The appearance of the spectrum suggests that the C IV is present in the form of a discrete absorption component, similar to those observed in B0.5–B5e stars. (*b*) UV spectral variability in the B6 IIIe-shell star *o* And. The *IUE* data shown here have been normalized to the flux at 1522 Å in order to properly compare the early small-aperture and more recent large-aperture spectrum. The spectrum obtained on 1981 day 320 has been shifted 1 Å in wavelength to compensate for being incorrectly processed as a small-aperture spectrum. The upper panel shows spectra obtained before, during, and after the 1980 shell episode. Circumstellar shell absorption is present in the 1978 day 237 and 1979 day 12 spectra in the form of a sharp absorption core in the Si II line at 1533.4 Å. The largest amount of line blanketing is present in the 1981 day 320 spectrum. C IV absorption is clearly present in the 1986 spectrum, obtained after the shell had dissipated. The lower panel shows additional spectra obtained during 1986 show small-amplitude changes in the amount of line blanketing by Fe II, particularly in the vicinity of 1560 Å. Strong and variable C IV absorption is present.

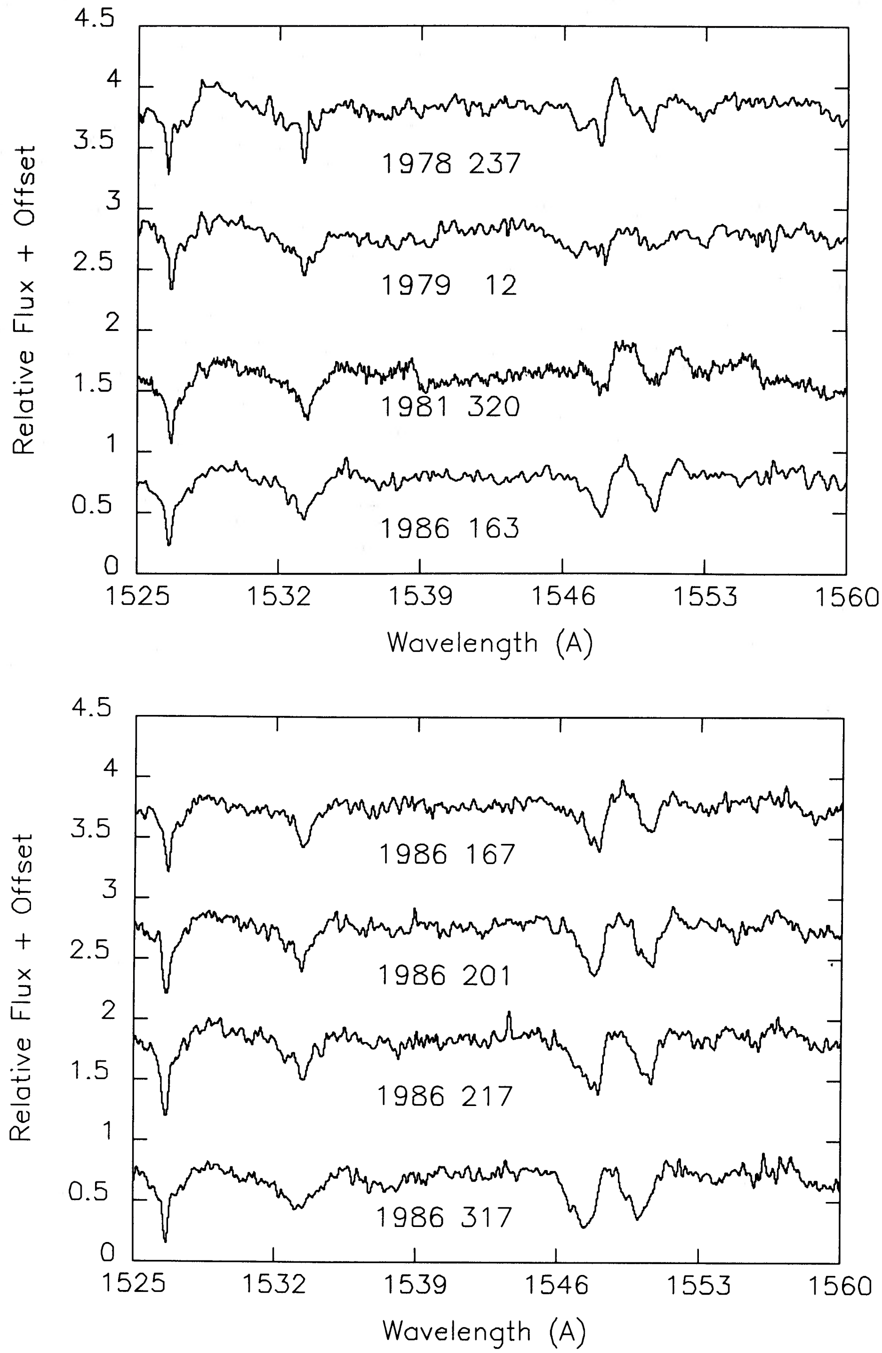

FIG. 4*b*

fact that the *IRAS* and *IUE* data typically were obtained at very different times. Variability in C IV absorption, and potentially also in the Si II absorption and IR color excesses, may also account for much of the scatter. The IR color excesses are also expected to be produced over a much larger volume, which may also dilute any correlations.

b) Hα *Line Profiles*

All of the program stars have published descriptions of the appearance of their Hα and sometimes Hβ line profiles (Dachs *et al.* 1981, 1986; Slettebak 1982; Andrillat and Fehrenbach 1982; Andrillat 1983; Barker 1984; Slettebak 1986; Ballereau *et al.* 1987; Hanushik, Kozok, and Kaiser 1988). While the available data are not contemporaneous with the *IUE* observations, some comparisons can be made. Be stars with $v \sin i$ above 140 km s^{-1} appear to have broad or double Hα profiles at least some of the time. No increase is seen in the Hα $v \sin i$ threshold for double emission profiles from that noted for B0.5–B5e stars (Paper I). A few of our program stars lacking highly ionized stellar winds (HD 22780, HD 26670, and HD 21551) are described by Slettebak (1982) as showing no emission. Further optical and ultraviolet observations will be required to determine whether all of these stars are truly Be stars or were merely in comparatively quiescent phases during the 1980s. Three of the program stars which did not show C IV absorption in Slettebak's data were observed in 1983 August with the CTIO 1.5 m telescope. Two of the stars, HD 149671 and HD 134481, showed weak or narrow double-peaked Hα emission, but no emission at Hβ. One star, HD 212581 (δ Tuc), showed weak double-peaked broad emission in both Hα and Hβ. CTIO observations made on 1984 September 11/12 showed a broad double-peaked emission profile inside a very broad absorption line and showed no obvious change from the 1983 observation. This star had not previously been known to be a Be star. No C IV or Si II shell absorption was detectable in any of our *IUE* spectra. Two stars with at most weak C IV absorption, HD 4552 and HD 23302, have been observed to show double emission profiles (Andrillat and Fehrenbach 1982). If the correlation between double Hα profiles and the presence at some epochs of highly ionized stellar winds in Be stars holds for Be stars independently of spectral type, these stars may have been observed by *IUE* during a period of wind quiescence. New UV observations will be needed to test this hypothesis.

c) Pulsation Characteristics

Pulsation data for B6–B9.5e stars are quite scarce, due in part to an initial expectation on the part of many observers that pulsation was unlikely to be important in the cooler Be stars, and there has been a consequent observational emphasis on the hotter stars. Penrod (1986) has found nonradial pulsation amplitude changes in HD 217675 similar to those observed in the early-type Be star λ Eri. McNamara (1987) found evidence for nonradial pulsation in three late-type Be stars in the Pleiades, two of which are included in our survey, and an absence of similar pulsation in normal B stars of comparable spectral type and luminosity class. Detection of nonradial pulsation in stars as cool as B8 implies that pulsation may be present, and potentially important, in all Be stars. Together with the $v \sin i$ threshold data, this result suggests that the combination of pulsation and rapid rotation may be responsible for much of the Be phenomenon.

d) Polarization

Four of our program stars (HD 58715, 91120, HD 209409, and HD 217675) were included in the polarimetric survey of bright northern Be stars by Poeckert, Bastien, and Landstreet (1979) and had intrinsic linear polarizations ≥0.1%. All of these stars have high $v \sin i$ and show Si II shell absorption. All of the stars, except for HD 209409, were also stars with C IV absorption. One of the program stars, *o* And, has been observed to undergo changes in both *B*-band and narrower band linear polarization in association with the development of a shell spectrum (Hayes 1982; Poeckert, Bastien, and Landstreet 1979). These results, while available only for a small fraction of the bright late-type Be stars, suggest that the correlation between significant intrinsic linear polarization and $v \sin i$ observed by Poeckert and Marlborough (1976) for early-type Be stars extends to the later Be stars.

VII. DISCUSSION

The pioneering survey of Slettebak and Carpenter (1983) indicated, and we confirm, the presence of highly ionized material in Be stellar spectra of all spectral types. Our detection of shortward-shifted discrete component absorption features in nine of our program stars suggests that this material is produced in a stellar wind, which attains velocities of at least a few hundred km s^{-1}. Detection of significant C IV profile variability in one of our program stars, HD 193911, together with previously reported line profile variations observed in B6 IIIe stars (Table 3), suggests that these stellar winds are similar to those observed in hotter Be stars, and rules out an interstellar origin for the C IV absorption. The velocities we observe for C IV in all of our program stars are less than the escape velocities from the photospheres. As a result, we cannot distinguish between mass levitation and true mass loss from the stellar gravitational well.

Slettebak and Carpenter (1983) suggested, and we confirm with our larger sample of Be stars, that the strength of the stellar winds in Be stars is a function of luminosity. The giant stars in our sample tend to have stronger winds than the less luminous, and less evolved luminosity class V–IV stars. This result, together with detection of discrete components and variability, suggests that radiation pressure plays an important role in driving these stellar winds, even though the stellar luminosities may be insufficient to initiate winds in these stars.

The *IUE* data suggest that highly ionized stellar winds are not present in luminosity class IV–III Be stars with $v \sin i$ significantly less than 150 km s^{-1} and that highly ionized stellar winds may not be present in luminosity class V B6–B9.5e stars with $v \sin i$ less than 200 km s^{-1}. Our sample contains too few spectra obtained over too short a time period to determine whether this effect is due to a real deficit of winds from 150 to 200 km s^{-1} or is an artifact of incomplete temporal sampling. If supported by additional observations, the difference in the $v \sin i$ threshold for C IV absorption may indicate that the threshold increases with increasing gravity. Such a result would indicate that the $v \sin i$ threshold for highly ionized stellar winds in A stars should be higher than for the Be stars. An increase in the $v \sin i$ threshold might be expected since the A stars are less luminous than the B stars. The only published survey of highly ionized material in A shell star spectra is due to Slettebak and Carpenter (1983), who included seven A stars in their survey. None of the A shell stars showed C IV or Si IV absorption in the single spectrum available to Slettebak and Carpenter. Also, with the exception of the lone A7 star, none of the stars had $v \sin i$ above 200 km s^{-1}. These observations are consistent with an increase in the $v \sin i$

TABLE 3

BE STARS WITH VARIABLE WINDS

HD	Spectral Type	$v \sin i$ (km s^{-1})	SWP Images		$W_{C IV}$(mÅ)	
			Minimum	Maximum	Minimum	Maximum
193911.........	B6 IVe	200	28102	29406	≤100	580
217675.........	B6 IIIe	260	28842	2939	550	1210
138749.........	B6 IIIe	320	19095	14431	120	1250

threshold for early- to mid-A stars but need to be confirmed by further observations of these stars, and by observations of other A stars.

A $v \sin i$ threshold in the range 150–200 km s^{-1} for the presence of highly ionized stellar winds coincides with the threshold for broad or double-peaked Hα profiles (Dachs *et al.* 1981, 1986; Andrillat and Fehrenbach 1982; Andrillat 1983; Barker 1984; Ballereau *et al.* 1987; Slettebak 1982) and with the presence of significant 12 μm color excesses (Waters 1986). Similar threshold for the optical and infrared spectral characteristics of Be stars were noted in Paper I for B0.5–B5e stars and are consistent with the few polarimetric observations and detections of nonradial pulsation in these stars. Taken collectively, the presence of winds exhibiting both the temporal variability and discrete absorption components characteristic of highly ionized stellar winds seen in earlier type Be stars, the presence of a $v \sin i$ threshold for the onset of these winds, and the agreement in $v \sin i$ threshold for the detection of infrared excesses and the presence of broad or double Hα profiles with that seen in C IV, imply that the same mechanism responsible for much if not all of the Be phenomenon in hotter stars is operating in stars with effective temperatures as cool as 10,000 K.

The presence of highly ionized stellar winds in stars as cool as 10,000 K poses several problems for our understanding of the outer atmospheres of intermediate-mass stars. The first problem is the identification of the mechanism capable of producing sufficiently strong winds or mass levitation to produce the observed extended envelopes. As noted in Paper I, radiation pressure alone is insufficient to drive detectable stellar winds from these stars, although if some other mechanism starts the outflow, radiation pressure may be sufficient to accelerate the wind to the observed maximum velocities.

We note that our lower temperature bound reflects the limits of our current survey. It is quite likely that highly ionized stellar winds may be present at high $v \sin i$ for cooler stars. As the stellar effective temperature decreases, detection of such winds becomes increasingly difficult, due to decreasing flux levels at 1550 Å, and to increasing spectral contamination by other species such as Fe II. Acquisition of *IUE* spectra of A stars with suitable S/N ratios at 1550 Å requires significant overexposure of the long-wavelength end of the SWP camera, a factor, coupled with the longer exposure times necessary for the observations, which has limited the number of such observations. Despite this observational difficulty, the UV may be the best part of the spectrum to search for evidence of Be-type activity in A stars. Slettebak (1986) has noted that for A0 and cooler stars, emission is not detected in Hα, except in the Herbig Ae stars, which are thought to be pre–main-sequence stars. The lack of Hα emission is due to decreasing contrast of the faint stellar envelope against the increasing photospheric absorption and implies that evidence for circumstellar material will be detectable in optical spectra only in stars showing shell absorption features or highly ionized stellar winds.

Bruhweiler, Grady, and Chiu (1989) have begun a preliminary survey of highly ionized stellar wind absorption in apparently normal late B and early A stars. They find C IV and Si IV absorption in A0–A1 stars not known to be interacting binaries only for $v \sin i \geq 200$ km s^{-1}. If these stars, many of which show Si II shell absorption features, are in fact A shell stars, this result would confirm the apparent increase in the $v \sin i$ threshold seen in our luminosity class V stars and would be consistent with the results of Slettebak and Carpenter (1983). If this study can be extended to later spectral types, it will be interesting to see at which spectral type highly ionized stellar winds becomes indistinguishable from chromospheres.

A second problem posed, and in fact intensified by our data, is the difficulty in ionizing material to temperatures greatly in excess of the stellar effective temperature. Kudritsky, Pauldrach, and Puls (1986) have found that improvements in the treatment of radiatively driven stellar winds in O stars produce dramatically improved agreement with the observed wind profiles and also duplicate the ionization observed in the stellar winds. It remains to be seen whether more accurate treatment of the radiative transfer in the nonspherical winds observed in Be stars will produce both the characteristic discrete components, and the observed ionization in stars ranging from $10,000 \leq T_{\rm eff} \leq 30,000$ K in the absence of strong radiation pressure initiated stellar winds. Modeling the outer atmospheres of Be stars should therefore provide many challenges for theoreticians.

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