ULTRAVIOLET SPECTROSCOPIC OBSERVATIONS OF SOME Be STARS
OF LATER TYPE AND A–F TYPE SHELL STARS

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ABSTRACT

High-dispersion IUE spectra of 18 later type Be and A–F type shell stars plus eight standard non-emission-line stars were analyzed for anomalous ionization and mass-loss effects. We find that superionization exists in Be stars of the latest spectral subtypes (B8–B9) and is strongest in the Be shell stars, but does not seem to be present in the A–F type shell stars. We also observe superionization in normal B-type stars as late as B5 and possibly B7–B8, but not later. Asymmetrical or violet-displaced resonance lines, suggesting mass loss, were observed in all of our Be program stars but one, and also in a number of our standard stars, but not in the A–F type shell stars. Lower limits to the mass-loss rates computed from Si iv lines range between $5.3 \times 10^{-12}$ and $3.5 \times 10^{-11} \, \text{M}_\odot \, \text{yr}^{-1}$, with the Be shell stars showing the largest values. Terminal velocities measured from the asymmetrical or violet-displaced resonance-line profiles show no clear correlation with ionization potential. Mass loss is correlated with luminosity and effective temperature in the sense that the B-type stars show mass-loss effects while the A-type stars do not, but seems to be uncorrelated with rotation. Emission was observed only in the Mg ii resonance doublet for two B5e stars in our sample. All of the A–F type shell stars show strong Fe ii and Mg ii absorption spectra relative to standard stars of similar spectral type. We conclude from our results that (1) although Be stars are nearly indistinguishable from normal B stars in the ultraviolet, there are differences in degree; and (2) the hot circumstellar envelope surrounding Be stars which gives rise to superionized lines and mass loss appears not to be as nearly equatorially confined as the cool circumstellar envelope.

Subject headings: stars: Be — stars: circumstellar shells — stars: mass loss — ultraviolet: spectra

I. INTRODUCTION

Early ultraviolet spectroscopic observations of Be stars concentrated on the stars of early type (see, e.g., papers in IAU Symposium 70 [1976]). More recently, these observations have been extended to cooler Be stars. Thus, Snow (1981) found mass-loss effects in the ultraviolet spectra of Be stars as late as B6, while Marlborough and Peters (1982) and Doazan (1982) detected anomalously high ionization (superionization) in Be stars as late as B7–B8. This investigation concentrates on the Be stars of later type, with observations also of the A- and F-type shell stars, which are believed to represent an extension of the Be phenomenon to later types. The object is to ascertain the degree to which mass loss and superionization effects persist to later types in the Be and A–F type shell stars, to compare the ultraviolet spectra of the program stars with those of normal, non-emission standard stars of similar spectral types, and to search for correlations of the effects found with stellar parameters such as $v \sin i$, luminosity, and effective temperature.

II. OBSERVATIONS

High-dispersion IUE spectra of 16 program stars and seven standard non-emission-line stars were obtained in both the short (~1200–1900 Å) and long (~1900–3200 Å) wavelength regions during several US 2 shifts in 1980–1982. Archival IUE spectra for two additional program stars and one additional standard star were obtained from the National Space Science Data Center (NSSDC).

The 18 program stars are listed in Table 1A in order of spectral type, with spectral types and rotational velocities ($v \sin i$) from the listing by Slettebak (1982). Stars with narrow lines (small $v \sin i$) were included, as well as stars with broad lines (large $v \sin i$). The former may be thought of as "pole-on" stars, if Be stars are interpreted according to Struve's (1931) rotational model, while the latter are then viewed nearly equatorially. These broad-lined stars also often show "shell spectra" (sharp absorption lines which arise from ground states or meta-
stable levels and presumably are formed in an equatorial shell)—examples at various spectral types were selected and are listed in Table 1A. It should also be noted that while the Be stars all show emission, at least at Hα, the A–F type shell stars in Table 1A do not—they are recognized as shell stars because of the simultaneous presence of rotationally broadened lines, on the one hand, and sharp lines arising from ground states and metastable levels, on the other.

The presence of the B3e shell star 48 Lib in a list of Be stars of later types also deserves some explanation. This star has been classified as B5 in the literature, but this classification was probably based on the attribution of its rather strong Si ii lines at 4128 and 4131 Å to the underlying star rather than to the shell. The correct spectral type appears to be close to B3, but we have retained 48 Lib as a program star because of its very interesting spectrum.

Table 1B lists the eight standard stars. These were selected to match, approximately, the spectral types of the program stars, and also to show a range of line broadening from sharp to broad. The spectral types are from Morgan, Abt, and Tapscott (1978), Morgan and Keenan (1973), or Johnson and Morgan (1953).
rotational velocities \((v \sin i)\) are from Slettebak et al. (1975) or are recent determinations by us based on that system.

### III. Superionization

An important result of ultraviolet observations of the hotter stars was the discovery in the spectra of some O- and B-type stars of atoms in higher stages of ionization than would be expected if normal photospheric radiation were the only ionizing source. Thus, lines of O vi, N v, C iv, and Si iv were observed in the spectra of stars with photospheres too cool to form these ions, calling for an additional source of ionization. This effect, usually called “superionization,” has been reviewed recently by Marlborough (1982) and Doazan (1982).

#### a) Be Stars and A-Type Shell Stars

Examples of superionization in the Be stars have been reported by a number of investigators, including Doazan (1982), Henize et al. (1976), Lamers and Snow (1978), Marlborough (1977), Marlborough and Snow (1976), Morton (1976, 1979), and Panek and Savage (1976). Recently, using IUE spectra of 23 Be Stars with spectral types O9–B8 and luminosity classes III–V, Marlborough and Peters (1982) reported the probable presence of N v lines in Be stars as late as B3, C iv lines as late as B8 (B7, according to Slettebak 1982), and Si iv lines also as late as B8 (also B7, according to Slettebak 1982). They compare these observational results with theoretical estimates of the coolest spectral types (based on the work of Lamers and Snow 1978) at which each ion would be expected under radiative equilibrium conditions, either in the photosphere or in a cool circumstellar envelope: O7 for N v, B1 for C iv, and B3 for Si iv.

One object of this investigation was to determine whether superionization extends to spectral types later than B7 in the Be stars and, indeed, whether the phenomenon reaches even into the A-type shell stars. Figures 1–6 illustrate the Si iv resonance doublet (multiplet UV 1) at 1393.755 and 1402.770 Å, and the C iv resonance doublet (multiplet UV 1) at 1548.188 and 1550.762 Å in the spectra of a number of the program stars.

In Figures 1 and 2, both the Si iv and C iv lines are strong in absorption in the spectrum of the B3 shell star 48 Lib. Note that there is some distortion of the profiles by lines of Fe II from the shell. Figure 3 shows that the Si iv doublet is clearly present in the three B5–B6e stars shown there and is stronger in the two shell stars (ψ Per and ι And) than in β Psc. The behavior of the C iv lines is consistent with that of Si iv: Figure 4 shows the lines clearly in the spectra of the same two B5–B6e shell stars but very weak or absent in β Psc.

Figures 5 and 6 show the Si iv and C iv doublets in some B6.5–B8e stars. The Si iv λ1393.755 line seems to be present in the three Be stars shown there, although other lines distort the spectrum somewhat. The C iv doublet also appears to be present in the spectra of η Tau and β Cyg B, but is very weak or absent in the B6.5e star φ And. The presence of both Si iv and C iv in the B8e star β Cyg B confirms the findings of Marlborough and Peters (1982) and Doazan (1982) that these lines persist into the late Be subtypes.

It is interesting that neither Si iv nor C iv is visible in the spectrum of the B8 shell star 28 Tau (Pleione). This
Fig. 3.—Spectral region including the Si iv resonance doublet at 1393.755 and 1402.770 Å (rest wavelengths indicated by arrows) in three B5-B6e stars and two B5 V standard stars.
Fig. 4.—Spectral region including the C iv resonance doublet at 1548.188 and 1550.762 Å (rest wavelengths indicated by arrows) in three B5–B6e stars and two B5 V standard stars.

object still has an extremely opaque shell, both in the visible and in the ultraviolet regions of the spectrum (see Figs. 16 and 21), which may affect the visibility of the Si iv and C iv lines. On the other hand, the late-type shell star 1 Del clearly shows Si iv λ1393.755 absorption. Its shell is not as dense as that of 28 Tau, but is sufficiently opaque in the visible portion of the spectrum to make the underlying star very difficult to classify. The estimated spectral type of 1 Del is B8–B9, making it one of the latest Be stars to show superionization effects.

Marlborough and Peters (1982) have noted some dependence of the strength of superionized lines in their B2e–B3e stars on $v \sin i$. Visual inspection of their spectra revealed that the range of strengths of C iv lines depends on $v \sin i$: while stars of large $v \sin i$ may have a range of C iv line strengths, stars of low $v \sin i$ seem to have only weak C iv lines. Although our sample is small, our spectra would seem to confirm this result. Inspection of Figures 3–6 shows that Be stars with small $v \sin i$ generally have weaker lines of Si iv and C iv than Be stars of the same spectral type with large $v \sin i$. A possible interpretation, as Marlborough and Peters (1982) point out, is that the hot component of the circumstellar envelope in which the superionized lines arise is not spherically symmetrical.

Is superionization also a feature of A-type shell spectra? The answer seems to be no. There is no trace of the C iv resonance doublet in the spectra of our A–F type shell stars. The Si iv lines are also probably not present, although there is a dip in the A-type shell star spectra near the Si iv λ1393.755 line. Figure 7 shows this wavelength region for the A1 iv shell star HR 4893, with the A0 V standard α Lyr also shown for comparison. The Fe ii lines at 1392.15, 1392.83, and 1393.21 Å are prominent, and probably account for the observed depression. This conclusion is strengthened by the fact that the other component of the Si iv doublet at 1402.769 Å appears not to be present. Unfortunately, our spectra are weak at these wavelengths, which makes the reality of broad features difficult to ascertain.

Of course, superionization may occur in the form of lines other than those of Si iv and C iv, and, indeed, in the A-type shell stars we might expect less ionized species than in the Be stars. In particular, if the Auger ionization mechanism proposed by Cassinelli and Olson (1979) is correct, the dominant stage of ionization in the stellar wind expected under radiative equilibrium conditions is doubly ionized by X-rays. Unfortunately, the resonance lines of C iii, Si iii, N ii–iv, and O ii–v are either outside the spectral range of IUE or too weak to detect in our IUE spectra, but we were able to examine the resonance lines of a number of other species:

1. Si ii multiplet UV 2 (1533.445 and 1526.719 Å). These lines increase in strength through the B-type stars.

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and are very strong at A2, with no significant difference between A-type shell stars and A-type standard stars. Other IUE spectra are too weak to show the lines for types later than A2.

2. C II multiplet UV 1 (1335.708 and 1334.532 Å). Our IUE spectra show these lines to strengthen from the middle to the late B types and remain strong through A2 (again, our sensitivity is too low for detection later than A2), with no appreciable difference between shell-type and normal stars.

3. Al II multiplet UV 2 (1670.787 Å). This line is weak at B3, strengthens through the B types, and becomes very strong in the range B8–A5 (A5 being the limit of our detection). The line is shown in A0–A5 stars in Figures 8 and 9, where again no significant difference between shell-stars and standard stars is apparent.

4. Al III multiplet UV 1 (1854.716 and 1862.790 Å). These lines are strong in the middle B-type stars, as shown in Figure 10, which also shows them to be somewhat stronger and asymmetrical in the two shell stars (ψ Per and α And), indicating contributions from a stellar wind. This will be discussed in the next section. The Al III lines exhibit a general weakening from B8 into the late A types, with no striking differences be-
b) The Standard Stars

An interesting result of this investigation is that some, but not all, of the standard, non-emission-line stars also show superionization effects in their ultraviolet spectra. Figures 1 and 2 show that the B3 V standard η UMa has Si IV but not C IV absorption, as might be expected at this spectral type. However, both the sharp-lined (ρ Aur) and broad-lined (ψ² Aqr) B5 V standards show strong Si IV absorption (Fig. 3), while the C IV doublet is weak or absent in both (Fig. 4).

For later spectral types it is very difficult to be certain whether superionized species exist. The broad-lined B7 V standard α Leo appears to show a broad and shallow Si IV λ1393.755 line, but the other component of the doublet is difficult to see. Figure 5 shows the depression at the position of the Si IV λ1393.755 line in the spectrum of ι And, but it is distorted by the presence of a number of Fe II lines. Si IV λ1402.769 seems not to be present. The C IV resonance doublet is not detectable in the spectrum of α Leo but may be present in ι And (see Fig. 6). Moving to still later types, Figure 7 shows a depression near Si IV λ1393.755 in the spectrum of the A0 V standard α Lyr, but this is probably due entirely to the confluence of the several Fe II lines in that wavelength region. There is no trace of the C IV resonance doublet, nor does the A2 V standard θ Leo show either Si IV or C IV absorption.
Fig. 8.—Wavelength region including the C i resonance multiplet (UV 2) centered at 1657 Å and the Al II resonance line (UV 2) at 1670.787 Å in three Al shell stars and an A0 V and A2 V standard star.
Be AND A–F SHELL STAR UV OBSERVATIONS

We have already discussed resonance lines of other species in the last section and found no strong evidence for unusual line strengths in either the program or standard stars of later types. Our observations thus show that superionization exists in standard, non–emission-line stars as late as B5 and, possibly, as late as B7–B8, but probably not later.

IV. STELLAR WINDS AND MASS LOSS

There is now a considerable literature on stellar winds and mass loss from Be stars. Marlborough (1982) and Doazan (1982) have summarized the ultraviolet data which have been used to infer or demonstrate mass loss in Be stars. Much of the work has centered on Be stars earlier than B2 (e.g., γ Cas, 59 Cyg, ξ Tau, φ Per). We note here two papers which include also Be stars of somewhat later type: Dachs’s (1980) IUE observation of eight bright Be stars, and the work of Snow (1981) based on Copernicus scans. The latter determined mass-loss rates for 19 Be stars from analysis of Si III and Si IV resonance lines, including objects as late as spectral type as B6.

Asymmetrical or violet-displaced resonance absorption lines, suggesting mass loss, were observed in all (except 28 Tau) of our Be program stars and also in a number of our B-type standard stars. This is shown for the Si IV and C IV doublets in Figures 1–6. In addition to these lines, stellar winds are also suggested in the profiles of resonance lines of Si II (multiplet UV 5), Al III (multiplet UV 1), and Mg II (multiplet UV 1) in some of our stars. Figure 10 shows the Al III resonance doublet at 1854.716 and 1862.790 Å in the spectra of three B5–B6e stars and two B5 standard stars. Note the asymmetrical structure.
in the shell stars ψ Per and o And, as well as in the broad-lined standard ψ² Aqr. On the other hand, the relatively sharp-lined (pole-on) Be star η Tau also shows a slight asymmetry in the same sense.

The standard B5 V star ρ Aur also shows asymmetrical resonance lines of other ions, including Si II and Mg II. The Mg II resonance doublet at 2795.528 and 2802.704 Å in the spectra of several Be and standard stars is shown in Figure 11, where the lines are clearly seen to be asymmetrical in the spectrum of ρ Aur.

Attempts to determine quantitatively the rates of mass loss associated with the winds from Be stars from ultraviolet line profiles have been summarized by Snow (1982a). A number of investigators, including Snow (1981), have utilized the atlas of theoretical P Cygni and stellar wind profiles by Castor and Lamers (1979). The latter assume resonance scattering and use the Sobolev approximation. They characterize the expanding envelope by two functions: the velocity law \( v(r) \) and the optical depth \( \tau(v) \). Thus, if \( v_\infty \) is the terminal velocity and \( R_* \) the photospheric radius, they define

\[
w = v/v_\infty, \quad x = r/R_*,
\]

and choose a velocity law of the type

\[
w = 0.01 + 0.99(1 - 1/x)^\beta \quad (\beta > 0).
\]

For an optical depth law Castor and Lamers adopt, for the radial optical depth \( \tau_{\text{rad}}(w) \), a law giving zero residual intensity at the violet edge of the line profile (i.e., at \( w = -1 \)):

\[
\tau_{\text{rad}}(w) = T(\gamma + 1)(1 - w_0)^{-1 - \gamma}(1 - w)^\gamma \quad (\gamma \geq 0),
\]

where

\[
T = \frac{\pi e^2}{mc} \frac{\lambda_0}{v_\infty} N_t,
\]

\( f \) is the absorption oscillator strength, \( \lambda_0 \) is the rest wavelength of the transition, and \( N_t \) the column density of the absorbing ion in the envelope. Castor and Lamers take \( w_0 = 0.01 \) for the flow speed at the base of the envelope, choose \( \beta = 0.5, 1, 2, \) and 4, and point out that the absorption part of their P Cygni profiles is very insensitive to the velocity law. Values of \( \gamma \) range between 0.5 and 4. They then give theoretical stellar wind profiles for a variety of combinations of \( \beta, \gamma, \) and \( T \).

Since the lines being studied may be formed in the photosphere as well as in the winds of the stars under consideration, it is necessary to correct for the presence of underlying photospheric profiles. Castor and Lamers suggest a procedure for this correction, which requires that the photospheric profile be known. We follow their
Fig. 11.—Spectral region including the Mg II resonance doublet at 2795.528 and 2802.704 Å (rest wavelengths indicated by arrows) in three B5–B6e stars and two B5 V standard stars.
method here and adopt also the procedure by Snow (1981), who derived the photospheric profiles directly from the observational data. He assumed that the long-wavelength side of a photospheric line profile will be virtually unaffected by the wind if it is optically thin, and folded the long-wavelength side of his observed profiles over to obtain an approximation to the underlying photospheric profile.

Still following Snow's (1981) application of the Castor and Lamers (1979) theoretical profiles, we calculated our mass-loss rates from

$$\dot{M} = 1.74 \times 10^{-18} \tau(w) \frac{v_{\infty}^2 R_*}{f \lambda_0 g A_E},$$

where $\tau(w)$ is calculated for $w = 0.5$, $v_{\infty}$ is in units of km s$^{-1}$, $R_*$ is in solar radii, $\lambda_0$ is in angstroms, $g$ is the ionization fraction for the observed species, $A_E$ is the assumed abundance of the observed element with respect to hydrogen, and the mass-loss rate is computed in solar masses per year.

Table 2 lists the atomic data for the lines analyzed in this investigation. The element abundances $A_E$ are solar values from the compilation by Ross and Aller (1976), while the wavelengths and $f$-values are from Morton (1978).

Table 3 lists the computed lower limits to the mass-loss rates for both the program stars and those standard stars which show asymmetrical or violet-shifted resonance line profiles. The stars are listed approximately in order of spectral type, from the hottest to the coolest. The Castor and Lamers (1979) parameter $\beta$ has the value of 0.5 for all cases and is not listed in Table 3 with their other parameters $\gamma$ and $T$. The stellar radii were estimated from the papers by Code et al. (1976) and Harris, Strand, and Worley (1963).

In addition to the unknown ionization balance in the stellar winds, other uncertainties affect the computation of mass-loss rates. These have been pointed out by Snow (1981) and, in a different context, by Kurucz (1974). One difficulty lies in the determination of the terminal velocity $v_{\infty}$, which has considerable uncertainty because the short-wavelength wing of the line profile merges very gradually into the continuum. Snow (1981) points out, however, that the error in estimating $v_{\infty}$ is partially cancelled out in the profile fitting process, with the mass-loss rate not affected radically. Another possible source of error is the blending of the short-wavelength wing of Si IV \(\lambda\lambda 1393.755\) with lines of Fe II, as can be seen in Figures 1 and 7. This effect would be especially troublesome for the shell stars and may lead to values of the terminal velocity which are too large and therefore also lead to excessive mass-loss rates. The assumption of spherical symmetry in the Castor and Lamers (1979) analysis may also not be valid for winds from Be stars, although the evidence is somewhat mixed at this time (see references in Snow 1981). Kurucz (1974), in a sample spectral synthesis near the C IV resonance doublet for a B2 star, has pointed out that the continuum level and equivalent widths will be affected by rotational line broadening. Furthermore, he shows that the central wavelengths of the rotated features are a function both of the blending with many weaker lines and the rotational velocity. Wavelength shifts produced in this way might then be erroneously interpreted as Doppler shifts due to mass motion in the stellar atmosphere.

Recognizing that our assumptions are the same as his, and that there is evidence (see Marlborough 1982; Doazan 1982) that Be winds are variable with time, it is nevertheless interesting to compare our results with those of Snow (1981). For three stars in common (48 Lib, $\psi$ Per, and o And), our terminal velocities are within 25% of his, and our mass-loss rates derived from the Si IV \(\lambda\lambda 1393.755\) line (adopting his ionization fractions) agree with his to within a factor of 2. On the other hand, Table 3 shows that our mass-loss rates as derived from the C IV lines are systematically lower and those from the Al III lines systematically higher than the Si IV mass-loss rates for a given star. A partial explanation may lie in the unknown ionization equilibria for all three elements. Also, we have already mentioned that possible blending of Fe II lines with the short-wavelength wing of

<table>
<thead>
<tr>
<th>Ion</th>
<th>$A_E$</th>
<th>$\lambda_0$</th>
<th>$f$</th>
<th>IP (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si IV</td>
<td>$4.5 \times 10^{-5}$</td>
<td>1393.755</td>
<td>1402.770</td>
<td>0.528</td>
</tr>
<tr>
<td>Si II</td>
<td>$4.5 \times 10^{-5}$</td>
<td>1190.416</td>
<td>0.251</td>
<td>16.35</td>
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<tr>
<td>C IV</td>
<td>$4.2 \times 10^{-4}$</td>
<td>1548.188</td>
<td>0.194</td>
<td>64.49</td>
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<tr>
<td>Al III</td>
<td>$3.3 \times 10^{-6}$</td>
<td>1854.716</td>
<td>0.539</td>
<td>28.33</td>
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<tr>
<td>Mg II</td>
<td>$4.0 \times 10^{-5}$</td>
<td>2795.528</td>
<td>0.592</td>
<td>14.97</td>
</tr>
</tbody>
</table>

Note: The wavelength columns are in angstroms, the ionization fraction column is dimensionless, and the IP column is in electron volts.
TABLE 3

TERMINAL VELOCITIES AND LOWER LIMITS TO THE MASS-LOSS RATES

<table>
<thead>
<tr>
<th>Star</th>
<th>( R_\star / R_\odot )</th>
<th>( \text{M}_\text{bol} )</th>
<th>( T_\text{e} ) (K)</th>
<th>Line</th>
<th>( \nu_\infty ) (km s(^{-1}))</th>
<th>( \gamma )</th>
<th>( T )</th>
<th>Lower Limit to ( M ) (( \text{M}_\odot \text{yr}^{-1} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>48 Lib</td>
<td>6</td>
<td>-4.1</td>
<td>18,000</td>
<td>( \text{Si iv} ) ( \lambda 1393.755 )</td>
<td>610</td>
<td>2</td>
<td>0.25</td>
<td>( 2.2 \times 10^{-11} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \text{C iv} ) ( \lambda 1548.188 )</td>
<td>490</td>
<td>1</td>
<td>0.25</td>
<td>( 5.2 \times 10^{-12} )</td>
</tr>
<tr>
<td>( \psi ) Per</td>
<td>6</td>
<td>-3.5</td>
<td>15,000</td>
<td>( \text{Si iv} ) ( \lambda 1393.755 )</td>
<td>530</td>
<td>2</td>
<td>0.5</td>
<td>( 3.5 \times 10^{-11} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \text{C iv} ) ( \lambda 1548.188 )</td>
<td>450</td>
<td>1</td>
<td>0.5</td>
<td>( 8.5 \times 10^{-12} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \text{Al iii} ) ( \lambda 1854.716 )</td>
<td>420</td>
<td>2</td>
<td>0.5</td>
<td>( 2.2 \times 10^{-10} )</td>
</tr>
<tr>
<td>( \beta ) Psc</td>
<td>4</td>
<td>-2.4</td>
<td>15,300</td>
<td>( \text{Si iv} ) ( \lambda 1393.755 )</td>
<td>480</td>
<td>0.5</td>
<td>0.1</td>
<td>( 5.3 \times 10^{-12} )</td>
</tr>
<tr>
<td>( \rho ) Aur</td>
<td>4</td>
<td>-2.4</td>
<td>15,300</td>
<td>( \text{Si iv} ) ( \lambda 1393.755 )</td>
<td>700</td>
<td>1</td>
<td>0.25</td>
<td>( 2.7 \times 10^{-11} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \text{Si ii} ) ( \lambda 1190.416 )</td>
<td>200</td>
<td>2</td>
<td>1</td>
<td>( 1.6 \times 10^{-11} )</td>
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<td></td>
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<td></td>
<td></td>
<td>( \text{Mg ii} ) ( \lambda 2802.704 )</td>
<td>230</td>
<td>2</td>
<td>0.25</td>
<td>( 2.1 \times 10^{-12} )</td>
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<tr>
<td>( \psi^2 ) Aqr</td>
<td>4</td>
<td>-2.4</td>
<td>15,300</td>
<td>( \text{Si iv} ) ( \lambda 1393.755 )</td>
<td>480</td>
<td>1</td>
<td>0.1</td>
<td>( 4.8 \times 10^{-12} )</td>
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<td></td>
<td>( \text{Al iii} ) ( \lambda 1854.716 )</td>
<td>320</td>
<td>1</td>
<td>0.1</td>
<td>( 2.2 \times 10^{-11} )</td>
</tr>
<tr>
<td>( \omega ) And</td>
<td>5</td>
<td>-3.1</td>
<td>14,000</td>
<td>( \text{Si iv} ) ( \lambda 1393.755 )</td>
<td>740</td>
<td>2</td>
<td>0.25</td>
<td>( 2.7 \times 10^{-11} )</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td>( \text{C iv} ) ( \lambda 1548.188 )</td>
<td>410</td>
<td>0.5</td>
<td>0.25</td>
<td>( 3.1 \times 10^{-12} )</td>
</tr>
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<td></td>
<td>( \text{Al iii} ) ( \lambda 1854.716 )</td>
<td>380</td>
<td>2</td>
<td>0.25</td>
<td>( 7.2 \times 10^{-11} )</td>
</tr>
<tr>
<td>( \text{HR} ) 7415</td>
<td>5</td>
<td>-2.5</td>
<td>14,000</td>
<td>( \text{Si iv} ) ( \lambda 1393.755 )</td>
<td>600</td>
<td>0.5</td>
<td>0.25</td>
<td>( 2.6 \times 10^{-11} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \text{C iv} ) ( \lambda 1548.188 )</td>
<td>300</td>
<td>0.5</td>
<td>0.1</td>
<td>( 6.8 \times 10^{-13} )</td>
</tr>
<tr>
<td>( \phi ) And</td>
<td>5</td>
<td>-2.9</td>
<td>13,700</td>
<td>( \text{Si iv} ) ( \lambda 1393.755 )</td>
<td>570</td>
<td>0.5</td>
<td>0.1</td>
<td>( 9.4 \times 10^{-12} )</td>
</tr>
<tr>
<td>( \eta ) Tau</td>
<td>5</td>
<td>-2.7</td>
<td>13,200</td>
<td>( \text{Si iv} ) ( \lambda 1393.755 )</td>
<td>550</td>
<td>0.5</td>
<td>0.1</td>
<td>( 8.7 \times 10^{-12} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \text{Al iii} ) ( \lambda 1548.188 )</td>
<td>450</td>
<td>0.5</td>
<td>0.25</td>
<td>( 3.8 \times 10^{-12} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \text{Al iii} ) ( \lambda 1862.790 )</td>
<td>230</td>
<td>1</td>
<td>0.1</td>
<td>( 2.8 \times 10^{-11} )</td>
</tr>
<tr>
<td>( \alpha ) Cyg</td>
<td>3.6</td>
<td>-1.6</td>
<td>13,400</td>
<td>( \text{Si iv} ) ( \lambda 1393.755 )</td>
<td>530</td>
<td>0.5</td>
<td>0.1</td>
<td>( 5.8 \times 10^{-12} )</td>
</tr>
<tr>
<td>( \beta ) Cyg B</td>
<td>3</td>
<td>-0.7</td>
<td>12,000</td>
<td>( \text{Si iv} ) ( \lambda 1393.755 )</td>
<td>590</td>
<td>0.5</td>
<td>0.1</td>
<td>( 6.0 \times 10^{-12} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \text{C iv} ) ( \lambda 1548.188 )</td>
<td>260</td>
<td>1</td>
<td>0.5</td>
<td>( 1.4 \times 10^{-12} )</td>
</tr>
<tr>
<td>1 Del</td>
<td>3</td>
<td>-1.0</td>
<td>11,500</td>
<td>( \text{Si iv} ) ( \lambda 1393.755 )</td>
<td>600</td>
<td>0.5</td>
<td>0.25</td>
<td>( 1.5 \times 10^{-11} )</td>
</tr>
</tbody>
</table>

Si iv \( \lambda 1393.755 \) may have resulted in systematically large Si iv mass-loss rates.

Based on computed mass-loss rates, Snow (1982b) found the three non-Be stars in his sample to be indistinguishable from the Be stars and suggested that the Be phenomenon itself is not uniquely linked to the presence of stellar winds. Although our mass-loss rates in Table 3 may be quite uncertain, there is some validity in comparing the stars listed among themselves, as Snow has done. We then also find no striking differences between the Be stars and the standard stars, with one exception: the five Be shell stars as a group appear to have somewhat larger mass-loss rate lower limits than the other stars in the table. This is also shown in Figures 12, 13, and 14. Obviously, more observations of both normal stars and Be stars are necessary to see whether this correlation is valid.

The terminal velocities \( \nu_\infty \) listed in Table 3 range between 200 and 740 km s\(^{-1}\), somewhat lower than either the values measured by Dachs (1980) or those listed by Marlborough (1982) for hotter Be stars. Our
measured terminal velocities show no clear correlation with ionization potential. In general, \( \nu_\infty \) is largest for Si IV, followed by C IV, Al III, Mg II, and Si II. Three Be stars in particular (\( \psi \) Per, \( \sigma \) And, and \( \eta \) Tau) show simultaneously asymmetrical resonance lines of Si IV, C IV, and Al III, with terminal velocities decreasing in that order. This result is not consistent with the usual assumption that ionization increases outward, in which case the C IV lines should show the largest terminal velocities. Again, however, the Si IV terminal velocities could be systematically high due to blending of Fe II lines with the short-wavelength wing of Si IV \( \lambda 1393.755 \).

We may attempt to correlate our mass-loss rates with various stellar parameters. Snow (1982b) has discussed the extension of OB star winds to lower luminosities, finding that luminosity is the dominant factor in driving the mass loss from Of to mid-B main-sequence stars. Specifically, he believes that the winds in Be stars may represent a straightforward extension of the OB star wind phenomenon to lower luminosities. Insofar as we find stellar winds in the Be stars of later type but not in the A–F shell stars, which are of lower luminosity than the Be stars, our results are consistent with Snow’s suggestion.

Is there a correlation between the mass-loss rates and the luminosities of our B-type stars? Figure 12 shows our lower limits to the mass-loss rates derived from the Si IV \( \lambda 1393.755 \) line for 12 stars versus their bolometric absolute magnitudes. The latter were estimated from the calibrations by Blaauw (1963) and Keenan (1963) and the bolometric corrections of Code et al. (1976) and Flower (1977), and are listed in Table 3. Again, a correlation seems to be present in the sense of Snow’s (1982b) conclusion: the more luminous stars show somewhat larger mass-loss lower limits. The dashed line in Figure 12 represents a least-squares fit to the data and has a correlation coefficient \( r = 0.50 \).

A correlation between mass loss and effective temperatures also exists in the sense that mass-loss effects are found in the B-type stars but not in the A-type stars. Within the B-type stars which show mass-loss effects, however, no correlation with effective temperatures is evident. This is shown in Figure 13, in which our mass-loss lower limits derived from the Si IV \( \lambda 1393.755 \) line are plotted versus effective temperatures for 12 stars. The latter were estimated from the papers by Code et al. (1976) and Flower (1977), and are listed in Table 3. A straight-line least-squares fit to the data in Figure 13 has a correlation coefficient \( r = 0.26 \), which we consider not to be significant.

Figure 14 shows our lower limits to the mass-loss rates derived from the Si IV \( \lambda 1393.755 \) line for the same 12 stars plotted against their rotational velocities \( v \sin i \). Here we might expect a correlation for the Be stars if stellar winds are related to the Be phenomenon, since the latter is clearly related to stellar rotation. No correlation is evident: a straight-line least-squares fit to the data in Figure 14 has a correlation coefficient \( r = 0.26 \).

Plots of bolometric absolute magnitudes, effective temperatures, and rotational velocities for the B-type stars versus lower limits to their mass-loss rates derived from C IV and Al III lines were also made. Although fewer observations were involved, these generally showed the same trends as the Si IV plots: no correlations of mass loss with effective temperatures and rotational velocities, but a mild correlation with bolometric absolute magnitudes.
V. EMISSION LINES

Be stars are characterized by Balmer emission in the visible portion of the spectrum, but show little or no emission in the ultraviolet. In a study of eight bright Be stars, selected because their optical spectra show very strong Balmer line emission, Dachs (1980) found emission in IUE spectra only in the wings of the Mg II resonance doublet and (for two stars only) in the wings of the Fe II resonance multiplets UV 1 and UV 2. Bruhweiler, Morgan, and van der Hucht (1982) observed Mg ii h and k emission in the spectra of the early-type Be stars ψ Per, υ Cyg, and γ Cas using the balloon-borne ultraviolet stellar spectrometer (BUSS), and suggested that a Bowen mechanism driven by Ly β is responsible.

Only two of our program stars show definite emission in the wings of the Mg II resonance lines: β Psc and ψ Per. These lines are shown in Figure 11. It is interesting that both are B5 stars, but ψ Per is a shell star with a large $v \sin i$, whereas β Psc has a small $v \sin i$ and is presumably a pole-on star. The Mg II resonance-line region in the spectrum of the B3 shell star 48 Lib is shown in Figure 15, along with the corresponding wavelength region in the standard B3 V star η UMa. Notice that the Mg II lines in 48 Lib are deep and show velocity structure, suggesting motions in the shell but no obvious emission. Dachs (1980) also found Mg II emission in 48 Lib to be uncertain.

In order to check for possible variability of the Mg II emission features in the spectra of the aforementioned stars, additional IUE spectra of ψ Per (LWR 9832 on 1981 February 1 and LWR 11990 on 1981 November 17) and β Psc (LWR 11989 on 1981 November 17) were obtained. No significant differences are discernable in these spectra, indicating no major changes in the Mg II emission over time periods of the order of a few months to a year for these stars.

VI. THE A–F TYPE SHELL STARS

The eight A–F type shell stars listed in Table 1A range in spectral types from A1 to F0. In the optical spectrum, all show rotationally broadened lines ($v \sin i$ ranging from 120 to 230 km s$^{-1}$) plus sharp lines which arise from ground states or metastable levels, the latter presumably formed in some kind of shell around the rapidly rotating underlying star. None of the stars show Balmer emission, although the hotter ones may have sharp Fe II lines in the optical spectrum (arising from metastable levels 2.6 to 2.8 eV above the ground state), the cooler ones are more likely to show the Ti II lines at 3685, 3759, and 3761 Å (arising from metastable levels ~ 0.6 eV above the ground state) and the H and K resonance lines of Ca ii.

We have already noted that the A–F type shell stars seem not to show superionized lines, nor do they have asymmetrical or violet-displaced resonance lines suggesting mass loss. Figures 22 and 23 show the strongest lines of Fe II multiplets UV 62, UV 63, and UV 64 of Fe II in the spectra of our A–F type shell stars plus standard stars. The only object which may have faint Fe II emission wings is the B5 shell star ψ Per (see Fig. 20, in which the short-wavelength wings of the Fe II multiplet UV 1 lines appear to be somewhat higher than the long-wavelength wings), but this is uncertain.
Fig. 16.—Spectral region including the Mg II resonance doublet at 2795.528 and 2802.704 Å (rest wavelengths indicated by arrows) in four B6.5–B8e stars and an B8 V standard star.
Fig. 17.—Spectral region including the Mg II resonance doublet at 2795.528 and 2802.704 Å (rest wavelengths indicated by arrows) in three Al shell stars and an A0 V and A2 V standard star.
FIG. 18.—Spectral region including the Mg II resonance doublet at 2795.528 and 2802.704 Å (rest wavelengths indicated by arrows) in four A5–F0 shell stars and an A5 III–IV standard star.
show ultraviolet emission lines, as may be seen in the
above figures and, for the Mg II resonance lines, in
Figures 17 and 18.
As might be expected, the Fe II lines which arise
either from ground states (e.g., multiplet UV 1) or from
metastable levels (see Figs. 22 and 23) are stronger,
deeper, and sharper in the A–F type shell stars than in
the standard stars. At least one star (β Pic) shows
structure in the Fe II line profiles, suggesting velocity
differences in the shell. Figures 17 and 18 also show that
the Mg II resonance lines (analogously to the Ca II H
and K lines in the optical region of the spectrum) are
stronger and deeper in the A–F type shell stars than in
the standard stars.

VII. SUMMARY AND CONCLUSIONS
We may summarize our results as follows:
1. Superionization in the Be stars extends to the latest
spectral subtypes (B8–B9) but does not seem to be
present in the A–F type shell stars.
2. The superionized lines in the Be stars appear to be
correlated with $v \sin i$ in the sense that they tend to be
stronger in stars with large $v \sin i$ than in stars with
small $v \sin i$ at a given spectral type. They are strongest
in the Be shell stars, which are also characterized by
large rotational velocities. These results suggest that the
hot component of the circumstellar envelope from which
the superposed lines originate is not distributed with
spherical symmetry, as has been suggested earlier by
3. Superionization is also observed in our sample in
normal, non–emission-line stars of spectral type as late
as B5 and, possibly, as late as B7–B8, but not later.
There is no obvious correlation in the strength of the
superionized lines with $v \sin i$.
4. Asymmetrical or violet-displaced resonance lines,
suggesting mass loss, were observed in all of our Be
program stars but one, and also in a number of our
standard stars, but not in the A–F type shell stars.
5. Computed lower limits to the mass-loss rates for
the Be stars are in the range $1.4 \times 10^{-12} - 2.2 \times 10^{-10} M_{\odot}$
yr$^{-1}$. The results from the Si iv λ1393.755 line range
between $5.3 \times 10^{-12}$ and $3.5 \times 10^{-11} M_{\odot}$ yr$^{-1}$. These
numbers are consistent with results for Be stars in
common with earlier investigators.
6. The five Be shell stars as a group show the largest
lower limits to the mass-loss rates of the stars in our
sample.
7. The terminal velocities measured from the asym-
metrical or violet-displaced resonance-line profiles range
between 200 and 740 km s$^{-1}$, but show no clear correla-
tion with ionization potential. This result is inconsistent
with the usual assumption that ionization increases out-
ward.
8. Mass loss and luminosity are correlated for the
stars in our sample in the sense that the B-type stars
show mass-loss effects while the (lower luminosity) A-
type stars do not. Among the B-type stars themselves,
the more luminous objects statistically have larger lower
limits to the mass-loss rates than the less luminous stars.
9. Mass loss and effective temperature are correlated
for the stars in our sample in the sense that the B-type
stars show mass-loss effects while the (cooler) A-type
stars do not. No correlation is found among the B-
type stars themselves.
10. Mass loss and rotation appear to be uncorrelated
for the stars in our sample.
Fig. 20.—Spectral region including the strongest lines of the Fe II multiplet UV 1 in three B5–B6e stars and two B5 V standard stars. The Fe II lines at 2585.876 and 2599.395 Å are indicated by arrows.
Fig. 21.—Spectral region including the strongest lines of the Fe II multiplet UV 1 in four B6.5–B8e stars and a B8 V standard star. The Fe II lines at 2585.876 and 2599.395 Å are indicated by arrows.
FIG. 22.—Spectral region including the strongest lines of the Fe II multiplets UV 62, UV 63, and UV 64 in three Al shell stars and an A0 V and A2 V standard star.
Fig. 23.—Spectral region including the strongest lines of the Fe II multiplets UV 62, UV 63, and UV 64 in four A5–F0 shell stars and an A5 III–IV standard star.
11. The only definite emission we observe is in the wings of the Mg II resonance doublet in two B5e stars in our sample—no Be stars of later type nor any of the A–F type shell stars show definite emission in any ultraviolet line.

12. All of our A–F type shell stars show strong ultraviolet Fe II and Mg II absorption spectra relative to standard stars of similar spectral type.

From these results, we draw the following conclusions:

i) Although Be stars are indeed nearly indistinguishable from normal B stars in the ultraviolet, as has been pointed out by Snow (1982c) and Doazan (1982), there are differences in degree: Be stars show superionization to later spectral types, generally have stronger superionized lines at a given spectral type, and, at least for the shell stars, show larger mass-loss rates.

ii) If correlations between the existence of superionized lines and mass loss versus $v \sin i$ exist for Be stars, they are weaker than correlations (from optical spectra and polarization measurements) involving the cool circumstellar envelope. This suggests that the latter is more nearly equatorially confined than the hot envelope which gives rise to the superionized lines and mass loss.

We are grateful to Mike Marlborough, Ted Snow, Paul Barker, and George Collins for very useful discussions. Some of this work was done while one of us (A. S.) was a visitor at the Institute for Astronomy of the University of Vienna, and the kind hospitality offered there is gratefully acknowledged. We thank also the IUE team at Goddard Space Flight Center for their help and cooperation, and the Ohio State University Instruction and Research Computer Center for providing computer time and facilities. The many drawings in this paper were prepared by Peter D. Stoycheff. We are also grateful to Mark Wagner for obtaining optical spectrograms of 17 Sex for us. Finally, we thank NASA for support via grant NAG 5-52.

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