THE FAR ULTRAVIOLET SPECTRA OF υ Cyg AND μ Cen

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Abstract. The spectra of the 'pole-on' Be stars υ Cyg and μ Cen have been observed in the region λλ 1000–1450 Å with the Princeton Ultraviolet Spectrometer on board the *Copernicus* satellite. The data include scans of intermediate resolution (0.2 Å) with U2 and high resolution scans (0.05 Å) of selected suspected shell lines with U1. The spectra of υ Cyg and μ Cen are compared with a complete intermediate resolution *Copernicus* scan of the equator-on Be star φ Per. The ultraviolet spectra of υ Cyg and μ Cen appear to be identical to those observed in non-Be stars of comparable ground-based spectral type. Neither emission nor shell features are observed. However, numerous strong shell features are seen in φ Per. An upper limit on the column density of hydrogen in our line of sight is computed for υ Cyg from the observed strength of a weak feature at λ 1130.4 Å identified as an Fe III shell line. Estimates for the dimensions of the circumstellar envelope are then obtained. Some implications of the strengths of the Fe III shell lines at λ 1130 Å observed in υ Cyg, μ Cen, φ Per, and other Be stars are discussed.

1. Introduction

The far ultraviolet spectra of the so-called 'pole-on' Be stars υ Cyg (B1.5Ve) and μ Cen (B2IVe) have recently been observed with the Princeton Ultraviolet Spectrometer on board the *Copernicus* satellite. A detailed study of both the ultraviolet and ground-based spectra of these stars is presently in progress. However, some early results from the investigation are interesting and worth reporting at this symposium.

In order to establish whether there are obvious differences between the ultraviolet spectra of the 'pole-on' Be stars and non-emission B-type stars of comparable ground-based spectral type, the *Copernicus* scans of υ Cyg and μ Cen were compared with those of λ Sco (B1V) and σ Sgr (B2.5V). Some possible ways in which the ultraviolet spectra of Be stars can differ from those of non-Be stars include (1) the presence of emission lines, (2) the presence of shell features, (3) veiling of photospheric features due to continuous Balmer emission, and (4) peculiarities in the photospheric line profiles which indicate significant line formation in the circumstellar envelope.

A major goal of this investigation was to search for shell features in the ultraviolet spectra of pole-on Be stars. In the far ultraviolet we might expect to find shell lines of C II, C III, N II, N III, Si II, Si III, S III, S IV, Fe II, and Fe III. The strengths of these shell lines can then be used to obtain an estimate of $N_H h$, the product of the density of hydrogen atoms times the path length, at polar latitudes. Thus, if one can determine a value for the mean density in the envelope from some other means such as the Balmer emission line strengths, the far ultraviolet shell lines can help shed some light on the geometry and/or physical extent of Be star envelopes.

With the above-stated goal in mind, μ Cen ($v \sin i \approx 200$ km s^{-1}) was chosen as a representative 'pole-on' Be star and υ Cyg ($v \sin i \approx 275$ km s^{-1}) as a Be star of intermediate inclination. In collaboration with Dr M. Plavec, the ultraviolet spectra

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of these stars were then compared with *Copernicus* scans of ϕ Per, a Be star which can be considered as being viewed nearly equator-on ($v \sin i \approx 400$ km s^{-1}). If the classical model for a Be star envelope is correct (i.e. a thick disk of material positioned about the equator of the star), then one should expect to see strong shell lines in ϕ Per, ones of intermediate strength in υ Cyg, and no shell features in μ Cen.

2. Observed Properties of μ Cen, υ Cyg, and ϕ Per

υ Cyg was designated as a 'pole-on' Be star by Slettebak (1949). Members of this class of objects typically have relatively narrow Balmer emission features with no conspicuous central reversals and relatively sharp photospheric features which suggest values of $v \sin i \leq 280$ km s^{-1}. If one assumes that all Be stars have equatorial velocities near 400 km s^{-1}, then the 'pole-on' Be stars have inclinations less than 45° to our line of sight. According to Slettebak (1949) and Slettebak and Howard (1955), $v \sin i = 280$ km s^{-1} for υ Cyg.

μ Cen is a member of the Scorpio-Centaurus association and according to Slettebak (1968) has a value of $v \sin i = 190$ km s^{-1}.

The He I photospheric features in ϕ Per are rotationally broadened to a high degree and show evidence of emission contamination. The value of $v \sin i$ is thus uncertain (see the Review paper given by Slettebak at this Symposium for a discussion of the accuracy of rotational velocities for the most rapidly rotating stars). A value of 400 km s^{-1} is tentatively assigned to ϕ Per.

μ Cen, υ Cyg, and ϕ Per have strong Hα emission features with no conspicuous structure. The Hα emission line profiles observed for these stars are shown in Figure 1. The spectrograms from which these profiles were obtained were taken with the

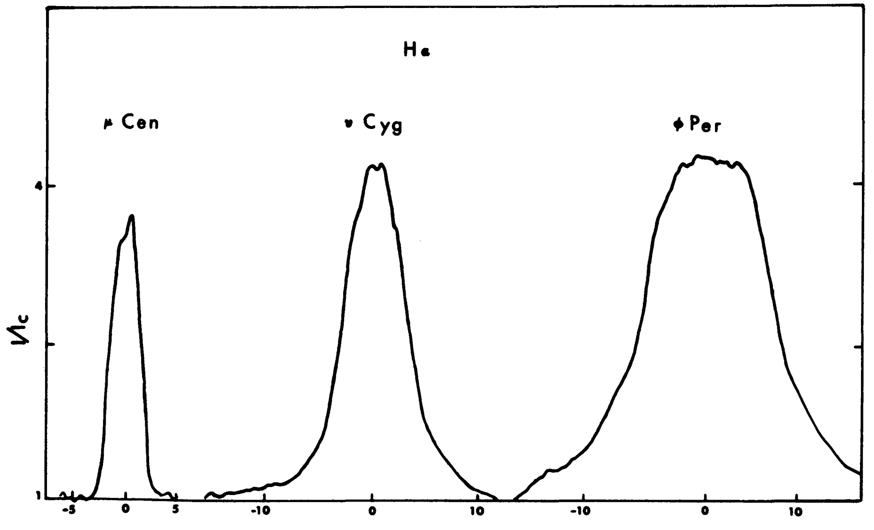

Fig. 1. Profiles of the Hα emission features seen in μ Cen, υ Cyg, and ϕ Per. The original dispersion of the spectrograms is 11 Å mm^{-1}.

Lick Observatory cooled 40 mm Varo image tube and the 24-in. (61 cm) Coudé Auxiliary Telescope (dispersion: 11 Å mm^{-1}). The peak intensities of the Hα emission lines are approximately four times the continuum value for all three stars. However, the widths of the features increase noticeably with the $v \sin i$ of the star. Thus, except for the fact that the Hα profile in ϕ Per does not show a deep central core, the Hα emission features are suggestive of the 'classical' model for a Be envelope. Variations in the 'fine structure' in the Hα emission profiles have been observed for μ Cen and ϕ Per. However, ten Hα plates of υ Cyg taken over the course of two years showed a constant profile.

We have also observed μ Cen, υ Cyg, and ϕ Per in the near infrared with the Lick Observatory Varo tube (dispersion: 23 Å mm^{-1}). All three stars show λ 8446 Å of O I in emission. This feature is formed via a fluorescence involving $L\beta$ (Bowen, 1947) and is discussed later in the paper in connection with the predictions for λ 1302 Å of O I. υ Cyg and ϕ Per also have emission at the higher order Paschen lines and emission of Fe II, O I λ 7774 Å, and the infrared Ca II triplet.

3. Observational Program

The Princeton Ultraviolet Spectrometer on the *Copernicus* satellite has been described in detail by Rogerson *et al.* (1973). The data for υ Cyg and μ Cen obtained for this project include continuous intermediate resolution (0.2 Å) scans with U2 ($\lambda\lambda$ 1000–1450 Å), continuous intermediate resolution (0.4 Å) scans with V2 ($\lambda\lambda$ 1800–3100 Å), and high resolution scans (0.05 Å) of selected features with U1. Although large fluctuations in the dark counts limited the usefulness of the V2 scans (see Rogerson *et al.*, 1973), the observed counting rates for U2 and U1 produced a fairly high signal-to-noise ratio. The observed noise is 1% and 3% of the signal in μ Cen and υ Cyg, respectively.

The features which were scanned with U1 in υ Cyg and μ Cen included lines of C II, N II, S II, S III, S IV, Si II, Si III, Si IV, Fe II, and Fe III which were tentatively identified as 'shell' features in the spectrum of ϕ Per. In addition, O I $\lambda\lambda$ 1302, 1305, and 1306 Å were scanned to search for emission and shell structure. Even though substantial interstellar contribution was suspected for some of the lines scanned with U1, they were observed with the anticipation of velocity differences existing between shell and interstellar features which would allow one to separate the components.

The U1 observations were programmed to block stray light from the scans (Snow, 1975). The stray light in U2 was removed with the aid of an algorithm developed by Bohlin (1975). Both stray light and particle background were removed with the aid of computer codes which exist at Princeton University.

4. Results

A comparison between the U2 scans of υ Cyg and μ Cen and those of the standards λ Sco and σ Sgr has revealed that the ultraviolet spectra of these 'pole-on' Be stars are apparently identical to those of non-emission B-type stars of comparable

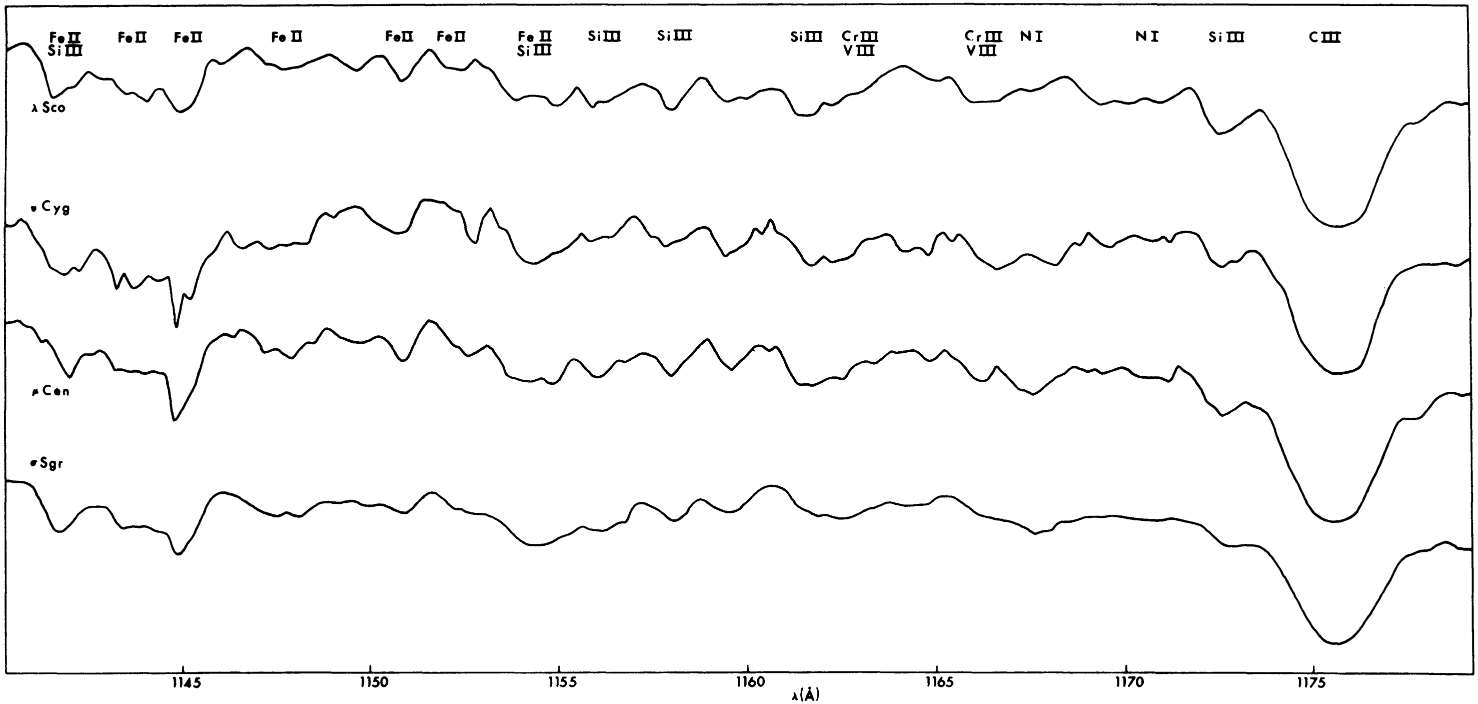

Fig. 2. The ultraviolet spectra of υ Cyg and μ Cen from $\lambda\lambda$ 1140–1180 Å compared with two standard stars, λ Sco and σ Sgr. The ions which significantly contribute to the stronger absorption features are indicated at the top of the diagram. The strong feature near λ 1175 Å is the C III sextuplet. Sharp features are interstellar.

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ground-based spectral type. Emission features are not observed in the far ultraviolet spectra of υ Cyg and μ Cen (not even $L\alpha$ and $L\beta$) and shell lines do not appear to be present. Some of the stronger photospheric features which are seen include: C II λ 1037 Å, N II λ 1084 Å, S IV λ 1073 Å, Fe III λ 1124 Å, C III λ 1176 Å, Si III λ 1206 Å, Si II λ 1265 Å, C II λ 1335 Å, and Si IV $\lambda\lambda$ 1394 and 1403 Å.

Shown in Figure 2 is an intercomparison between the ultraviolet spectra of μ Cen, υ Cyg, λ Sco, and σ Sgr in the interval $\lambda\lambda$ 1140–1180 Å. The ions which contribute substantially to the stronger photospheric lines are listed above the features. Certainly, the differences between the spectra are small. The values of $v \sin i$ for λ Sco and σ Sgr (250 and 200 km s^{-1}, respectively) are comparable to those observed for υ Cyg and μ Cen.

The ultraviolet line strengths in υ Cyg compare well with those in λ Sco. The temperature and log g for υ Cyg which are indicated by the ground-based data are 24 000 K and 3.8, respectively (Peters, 1976) while the temperature of λ Sco appears to be near 23 500 K (on the scale of the Princeton model atmospheres). From an inspection of the U2 scans, it appears that the temperature of μ Cen is between that of λ Sco and σ Sgr. An analysis of the ground-based spectrum of μ Cen suggests that $T_{\rm eff} \approx 20\,000$ K and log $g \approx 3.5$. Similarly, the $T_{\rm eff}$ for σ Sgr is near 18 000 K.

The analysis of the ultraviolet spectrum of υ Cyg is complicated by the fact that numerous strong interstellar features (including H_2) are present. These interstellar lines could easily mask weak shell components in the U2 scans (they can be separated in the U1 scans, however). The interstellar features are weak in μ Cen.

The projected rotational velocities for υ Cyg and μ Cen indicated by the weaker photospheric features in the far ultraviolet appear to be consistent with those suggested by the ground-based features. The line widths for the weaker features are one-fourth the values observed for the features near λ 4000 Å. Of course, the ultraviolet features which have substantial Stark broadening have much larger half-widths.

The values for the ultraviolet flux of υ Cyg and μ Cen appear to be comparable to those of non-Be stars of similar ground-based spectral type. The predicted counting rates for U1 and U2, which were based upon those observed for standard stars, were identical to those which were observed.

The O I resonance line λ 1302 Å was observed in υ Cyg and μ Cen both with U1 and U2. This transition is the final step of a set of three which are activated by a fluorescence with $L\beta$ (Bowen, 1947). The sequence proceeds in the following manner: O I λ 1025 Å (2^3P–3^3D) → λ 11287 Å (3^3D–3^3P) → λ 8446 Å (3^3P–3^3S) → λ 1302 Å (3^3S–2^3P). λ 8446 Å is observed to be moderately strong in emission in υ Cyg and weak in emission in μ Cen (1.25 and 1.05 times the local continua, respectively). The U2 and U1 scans of λ 1302 Å in υ Cyg and μ Cen along with the profiles of λ 8446 Å (from Varo image tube spectrograms taken at Lick Observatory) are presented in Figure 3. No obvious emission is present at λ 1302 Å in either star. The strong absorption features are interstellar O I λ 1302 Å.

Based on the strength and width of λ 8446 Å in υ Cyg the predicted intensity and width of λ 1302 Å in this star are 1.03 I_c and 1 Å, respectively, and are, therefore, slightly below the limit of detectability on U2 scans. The predicted strength of λ 1302 Å in μ Cen is lower than that for υ Cyg. However, the strength and width of

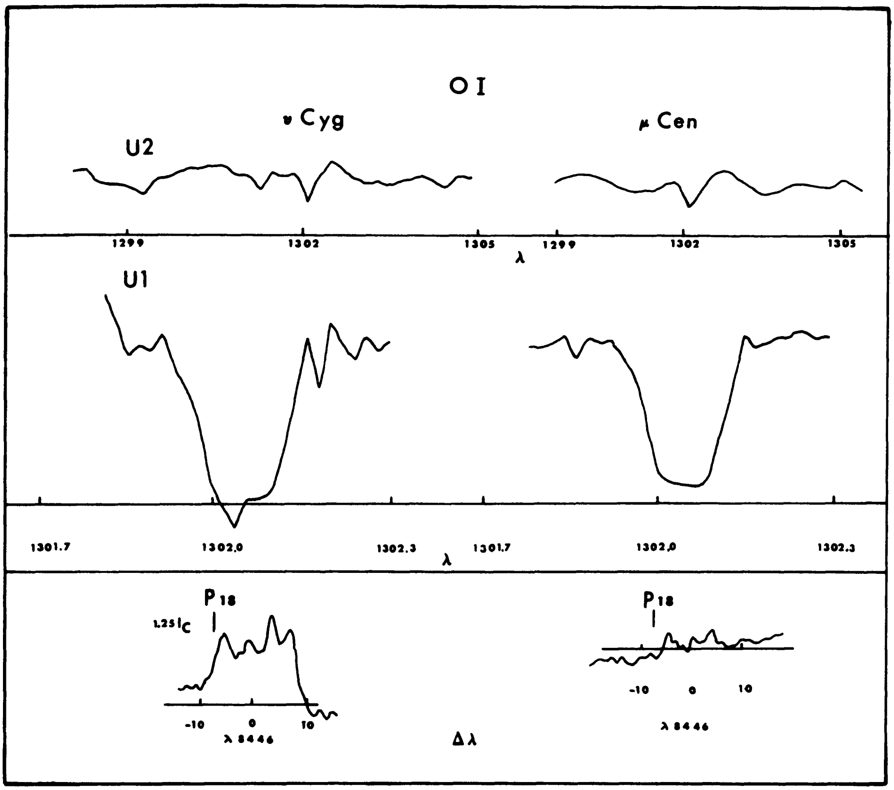

Fig. 3. U1 and U2 scans of υ Cyg and μ Cen in the region including λ 1302 Å of O I. Shown below these observations are the features of O I λ 8446 Å which are seen in these stars.

λ 8446 in ϕ Per (1.7 I_c and 13 Å, respectively) predict a peak intensity of 1.07 I_c and a width of 2 Å for λ 1302 Å in this star. No emission at λ 1302 Å is observed on a U2 scan of ϕ Per, however, even though the predicted strength for the feature is well above the limit of detectability.

The search for shell features in the far ultraviolet spectra of the 'pole-on' Be stars υ Cyg and μ Cen produced negative results. Whereas numerous shell features are observed in ϕ Per, no shell lines have been identified with certainty in the spectra of the 'pole-on' stars considered in this program. U1 scans reveal the *possible* presence of weak shell absorptions ($\approx$20 mÅ) of S II λ 1014 Å and Fe III λ 1130 Å in υ Cyg.

U2 scans of μ Cen, υ Cyg, ϕ Per, and the standard λ Sco in the region of Fe III, multiplet 1, are intercompared in Figure 4. Note the great strength of the Fe III shell features in ϕ Per compared to the conspicuous absence of similar features in υ Cyg and μ Cen. The Fe III lines in υ Cyg and μ Cen are photospheric features.

An upper limit on the column density of Fe III can be computed for υ Cyg from the strength of the weak λ 1130 Å feature observed on the U1 scan. The f-value quoted by Kurucz and Peytremann (1975) was used for the computation. Since $N(\text{Fe III}) \approx N(\text{Fe})$ and $N(\text{Fe}) \approx 10^{-5} N_{\text{H}}$, we obtain a value of 5×10^{19} cm^{-2} for $N_{\text{H}}h$. If $N_{\text{H}} \approx 10^{10}$ cm^{-3}, then $h \approx 5 \times 10^9$ cm or about 0.1 $R_\odot$! If $N_{\text{H}} \approx 10^8$ cm^{-3}, then $h \approx 10\ R_\odot$ or

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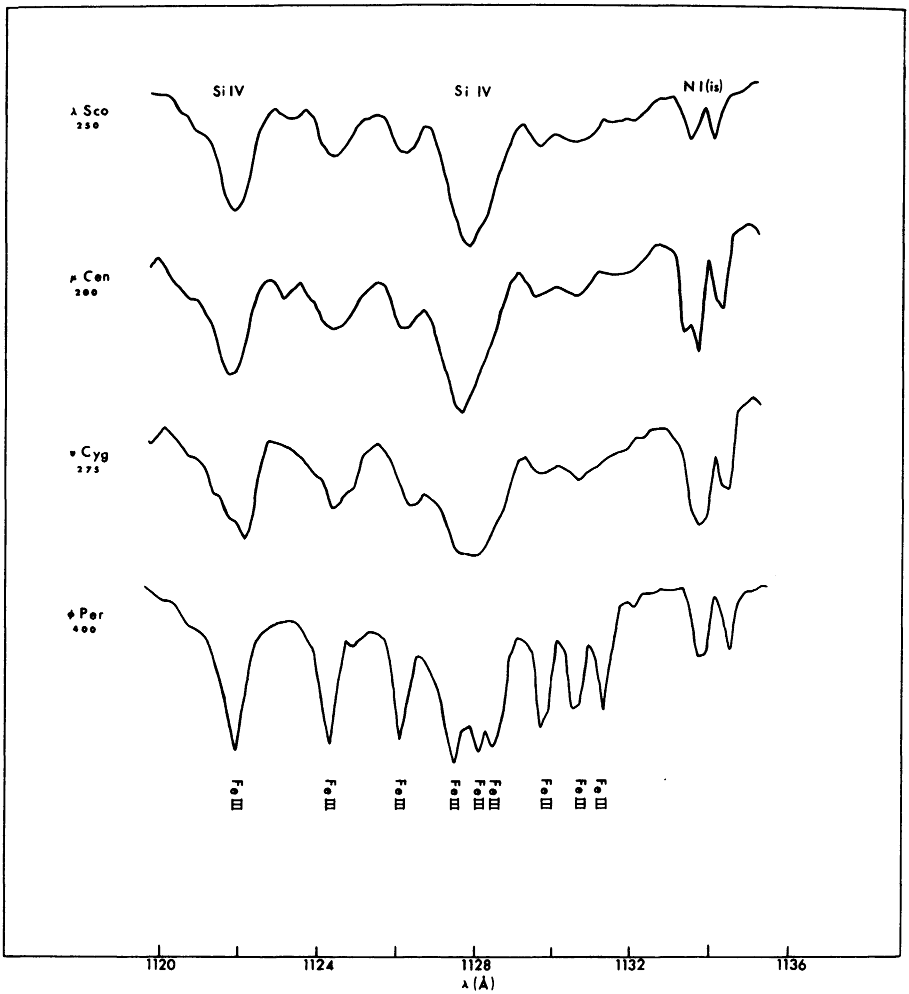

Fig. 4. The spectra of the Be stars μ Cen, υ Cyg, and φ Per and the standard λ Sco in the vicinity of multiplet 1 of Fe III. Approximate values of $v \sin i$ for each star are quoted below their labels. Shell-type absorptions are seen for Fe III in φ Per. The sharp N I features are interstellar in origin.

$1.0 R_*$! Therefore, the absence of strong Fe III shell absorptions in υ Cyg suggests that virtually all of the material in its circumstellar envelope is located outside of our line of sight.

The volume emission measure for υ Cyg [obtained from the equivalent widths of the Hγ and Hδ emission features with the aid of Wellman's formula quoted in Pagel (1960)] is $N_{\text{ion}} N_e V \approx 5 \times 10^{57}$ cm^{-3}. If $N_{\text{ion}} = N_e \approx 10^{10}$ cm^{-3} and if the material is confined to a thick disk with a height of 1 R_*, then $R_{\text{env}} \approx 13$ R_*. If the cross-section of the envelope is more wedge-shaped with inner and outer heights of 2 R_* and 10 R_*, respectively, then $R_{\text{env}} \approx 5$ R_*. The observations of the ultraviolet Fe III shell lines in υ Cyg are not inconsistent with the model for a Be star envelope suggested by Marlborough (1969).

5. Further Comments on the Fe III Shell

The comparison between the ultraviolet spectra of the 'pole-on' Be stars υ Cyg and μ Cen and the equator-on Be star ϕ Per would seem to support the 'classical' model for the envelope of a Be star in that strong shell absorptions are present in the latter object but absent in the former ones. In order to determine whether it is true, in general, for Be stars that the strength of the shell features in the far ultraviolet correlate with the projected rotational velocity of the star, U2 scans of other Be stars which exist in the Princeton files were examined. The region of the Fe III shell lines (λ 1130 Å) was particularly useful since the Fe III features can be strong and λ 1130 Å is near the peak sensitivity for U2. The results are given in Table I. The

TABLE I

Strength of the ultraviolet Fe III shell in Be stars

Star	Observer	$v \sin i$[a]	Strength
γ Cas	Marlborough[b]	300 km s^{-1}	None
ϕ Per	Plavec[b]	400	Strong
48 Per	Snow	200	Very weak
ζ Tau	Heap[b]	275	Strong
μ Cen	Peters[b]	200	None
η Cen	Burton/Evans[b]	300	Weak
χ Oph	Snow	100	Moderate-weak
υ Cyg	Peters[b]	275	None
31 Peg	Marlborough[b]	100	Moderate-strong

[a] Approximate values based upon those quoted in Uesugi and Fukuda (1970).

[b] Guest Investigator using the Princeton Ultraviolet Spectrometer on the *Copernicus* satellite.

estimated strengths quoted for the Fe III shell features are qualitative values only and may in some cases contain significant contributions from photospheric Fe III lines. It can be seen, however, that a strict correlation between Fe III shell strength and $v \sin i$ does not exist. We find rapidly rotating Be stars ($v \sin i \geq 300$ km s^{-1}) which show no shell (γ Cas), a weak shell (η Cen), and a strong shell (ϕ Per). Whereas the Fe III shell features are effectively absent in υ Cyg, they are strong in ζ Tau even though the projected rotational velocities for both objects are comparable. Even the pole-on Be star 31 Peg appears to have a moderately strong Fe III shell.

Thus, either some Be stars have a substantial amount of material at their polar latitudes or Be stars have a wide range in their intrinsic rotational velocities (the value of $v \sin i$ may not be indicative of the inclination of the star's equator to our line of sight). It is difficult to reconcile a classical model for a Be star envelope which is based upon the concept of forced rotational ejection with the observations of 31 Peg, however. An equatorial velocity of 100 km s^{-1} hardly seems adequate enough to supply a circumstellar disk with material.

This study of the ultraviolet spectra of υ Cyg and μ Cen combined with the observations of the Fe III shell in other Be stars suggests that Be stars are not a homogeneous group of objects. Perhaps the strengths of the Fe III shell lines observed in the far ultraviolet spectra of Be stars can be used in conjunction with the strengths and/or profiles of other envelope features and the photospheric parameters for the star to help shed some light on the geometry, physical structure, and origin of the various types of Be envelopes.

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