ULTRAVIOLET OBSERVATIONS OF Be STARS

(*Review Paper*)

SARA R. HEAP

Laboratory for Optical Astronomy, NASA Goddard Space Flight Center, Greenbelt, Md., U.S.A.

1. Introduction

The history of ultraviolet studies of Be stars is barely ten years old. However, in the last decade, twelve major space experiments have observed Be stars in the ultraviolet region of the spectrum, and ultraviolet data for over 30 Be stars are now available in the literature. Table I shows some of the characteristics of the experiments. They include two rockets, five astronomical satellites, three manned satellites, and one planetary probe. Except for the rocket experiments, they are primarily survey instruments, which have provided ultraviolet data on early-type stars in general, and these data have proved to be extremely useful as standards of comparison for Be stars. Of the twelve spacecraft, two are presently operating: *Copernicus* and ANS. The two experiments complement one another very nicely in that the ANS experiment can obtain absolute continuous flux distributions, while the Princeton experiment can obtain high-resolution line spectra for the brighter Be stars.

Table II shows those bright Be stars, which have been observed in the ultraviolet, and for which there are explicit published data. For most stars, the coverage has been spotty, but for a few stars such as ζ Tau and γ Cas, the ultraviolet data are complete in the sense that absolute continuous fluxes as well as high-resolution line spectra are available, often from more than one source, so that cross-checks can be made and the extent of variability, if any, determined.

Rather than organize this review, experiment by experiment, or star by star, I would like to divide this review into four parts, each one describing an area of study in which ultraviolet data have proved useful (or should prove useful) in coming to an understanding of Be stars. The four areas are: (1) spectral classification and the determination of the stellar atmospheric parameters, (2) evidence for mass loss and the formation of circumstellar shells around Be stars, (3) the effects of very rapid rotation on the properties of Be stars, and (4) the constituents and physical properties of the shells surrounding Be stars. In each of these areas, I shall use one star as a primary example, in the belief that the accumulation and comparison of many data on one star lead to a more certain understanding of the nature of a Be star than only one datum per star for many stars. The example I shall use is ζ Tau because it has been studied most intensively and because it has many characteristics in common with other Be stars: its emission lines are strong, its shell spectrum is very rich, and its infrared excess is sizeable. I do not wish to imply that it typifies Be stars in general. In all probability, it does not. This is something we can assess after hearing all the papers at this Symposium.

A. Slettebak (ed.), Be and Shell Stars, 165–178.

TABLE I

Space experiments which have observed Be stars

Experiment	(Satellite)	Launch date	Range	Resolution	Reference
A. Filter Photometry					
———	(1964 83C)	1964	1376 Å		Smith (1967)
Celescope	(OAO-2)	1968	4 filters		Davis *et al.* (1972)
U. Wisconsin	(OAO-2)	1968	12 filters		Code *et al.* (1970)
B. Low Resolution Spectrophotometry					
U. Wisconsin	(OAO-2)	1968	1800–3800 Å	20 Å	Code *et al.* (1970)
			1050–2000	10	
UVS	(Mariner 9)	1971	1150–3400	15	Lillie *et al.* (1972)
			1150–1650	7.5	
S2/68	(TD1)	1972	1350–2500	35	Boksenberg *et al.* (1975)
S-169	(Apollo 17)	1972	1180–1680	10	Henry *et al.* (1975)
Orion-2	(Soyez 13)	1973	2000–4000	variable	Gurzadyan *et al.* (1974)
UV Exp.	(ANS)	1974	1500–3300	150	van Duinen *et al.* (1973)
S-019	(Skylab)	1974	1300–5000	variable	Henize *et al.* (1976)
C. High Resolution Spectroscopy					
S-59	(TD1)	1972	2060–2160 Å	1.9 Å	de Jager *et al.* (1974)
			2490–2590	2.3	
			2770–2870	1.8	
Princeton U.	(Copernicus)	1972	~750–1500	0.2, 0.05	Rogerson *et al.* (1973)
			~1500–3200	0.4, 0.10	Bohlin (1970)
———	(Rocket)	1968	1060–2130	2.0	Bohlin (1970)
———	(Rocket)	1972	1100–2040	0.1	Heap (1975)

TABLE II

Bright Be stars observed in the ultraviolet

Star	Spectral type	Reference				
		OAO-2	*Copernicus*	TD 1	Mariner 9	Other
o And	B6p	3		10, 18	12	
π Aqr	B1 Ve	13			12	
ι Ara	B2 IIIe					9
α Ara	B2 Vne	13				
ρ Car	B4 Vne	13				
f Car	B3 Vne					15
γ Cas	B0.5 IVe	5, 13	17	11	12	2, 8, 15
ε Cas	B3 Vp	3			12	
δ Cen	B2 IVne	13		11		
η Cen	B1.5 Vn	13	4, 17			9, 15
μ Cen	B2 IV–Ve	3, 13	14, 17			
α Col	B8 Ve	13		11, 18		
ω CMa	B2 IV–Ve			11		
κ CMa	B2 Ve	13		11		9
υ Cyg	B2 Ve	3	14		12	
59 Cyg	B1.5 Ve	13				
60 Cyg	B1 Vnep	5				9
κ Dra	B7 e	3		11, 18		15
α Eri	B3 Vp	13		11		15
ν Gem	B7 IVe			18		
8 Lac	B1 Ve					9
48 Lib	B5 IIIp	3				
β Mon A	B3 Ve			11		
χ Oph	B1.5 Ve		16			
ω Ori	B2 III	3, 13				
25 Ori	B1 Vn	13				
λ Pav	B1 Ve			11		9, 15
31 Peg	B2 IV–Ve		17			
ϕ Per	B1 pe	13	17		12	9
ψ Per	B5 e				12	
48 Per	B3 Ve		17			
o Pup	B0 V:pe					9
ζ Tau	B4 IIIp	3, 13	17	11, 1, 6	12	7, 8, 15
η Tau	B7 III	3				
HD 28497	B1.5 Ve		17			
HD 58978	B0 VI?pe					9
HD 120991	B2 IIIe					9
HD 135160	B0.5 Ve					9
HD 200775	B3 IV–Ve			19		
HD 217050	B4 IIIpe	3				

1. Beeckmans (1975).
2. Bohlin (1970).
3. Bottemiller (1971).
4. Burton and Evans (1976).
5. Coyne (1972).
6. Delplace and van der Hucht (1976).
7. Heap (1975).
8. Heap and Stecher (1974).
9. Henize *et al.* (1976).
10. Kondo *et al.* (1975).
11. Lamers and Snijders (1975).
12. Molnar (1975).
13. Panek and Savage (1975).
14. Peters (1976).
15. Smith (1967).
16. Snow (1975).
17. Snow and Marlborough (1976).
18. Underhill and van der Hucht (1976).
19. Viotti (1975).

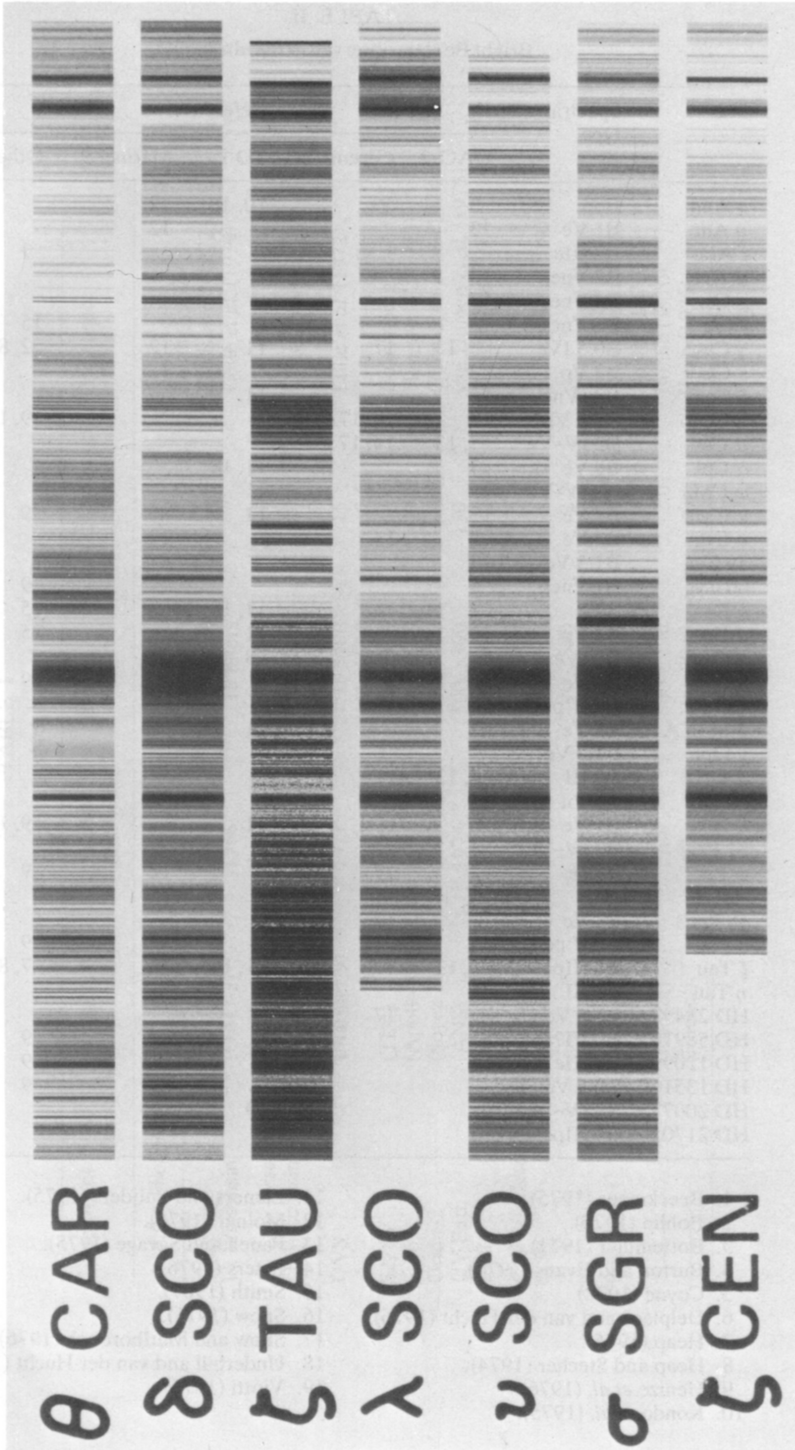

Fig. 1. Photographic Reconstruction of U2 Spectrograms from *Copernicus*. The spectra have been arbitrarily normalized, and noise has been added for simulation purposes.

2. Spectral Classification

A system for ultraviolet spectral classification has not been fully worked out as yet, but it may prove a good deal easier and more accurate – at least for Be stars – than that worked out for the visual region of the spectrum. Figure 1 shows a reconstruction of several U2 spectra of 7 B-type stars that were obtained by the Princeton experiment on *Copernicus*. The spectral interval covered here goes from λ 1050 Å on the left to λ 1420 Å on the right. All the stars have published projected rotational velocities of around 200 km s^{-1} except for υ Sco whose $v \sin i \cong 30$ km s^{-1}, and ζ Tau whose published $v \sin i \cong 300$ km s^{-1}. The spectral types of the stars range from B0.5 at the top to B2.5 at the bottom. One Be star, ζ Tau, is also shown here for comparison. The most prominent line, of course, is Lyman alpha at λ 1216 Å. The strength of this line is a measure of the interstellar column density of hydrogen. This quantity should be a great help in the study of Be stars because Bohlin (1975) has found a tight correlation between the interstellar hydrogen column density and the color excess, $E(B-V)$. This means that it should now be possible to estimate the intrinsic color of a Be star (at least those with early *B* spectral types) with corrections for interstellar extinction based on the strength of Lyman alpha line.

One of the main advantages of the ultraviolet is that it contains strong lines of abundant elements, e.g., C III λ 1175 Å, N III λ 1183–5 Å, Si III λ 1206 Å, C II λ 1334–5 Å, Si IV λ 1394, 1403 Å. These lines are especially useful in determining the atmospheric properties of Be stars for several reasons. First, since they are strong lines, they are easily and accurately measured, even in stars with high projected rotational velocities. Most of these strong lines are resonance lines of abundant elements so that their associated atomic data are relatively reliable. Secondly, sometimes more than one stage of ionization of an element is present (as is the case here with Silicon, where both Si III λ 1206 Å and Si IV λ 1394, 1403 Å are present) so it is possible to use them for ionization balance tests. Figure 1 shows that Si III λ 1206 Å is very sensitive to spectral type: it is quite strong in the B2.5 stars and very weak in the B0.5 stars. Thirdly, some of these lines, like the Si IV resonance lines, belong to high ionization states so they are not contaminated by a shell component. Fourthly, the very strong lines are useful in determining the velocity field in the atmospheres of Be stars. Since the lines are very strong, they are formed in the outermost layers of the atmosphere, and so they are good indicators of mass motions in these outermost layers. Finally, some of these lines are good measures of projected rotational velocity.

Zeta Tau is a case in point, illustrating – sometimes with surprising results – some of those benefits that I have just outlined. One result is that the observed ionization-balance of Si III vs Si IV and C III vs C IV is best matched by Mihalas' (1972) model with the parameters $T = 27\,500°$ and $\log g = 4.0$. This value for the temperature is much higher than what would be expected from the most recent estimate of its spectral type, which is B4 III. The line profiles computed from this model are compared to the observed profiles in Figure 2. It is evident that the observed lines best fit the profiles for deficient C and Si. Another surprising result is that the stellar lines are all shifted to shorter wavelengths. The exact amount is shown under the word, 'Shift' in Figure 2. These shifts correspond to outward velocities of up to

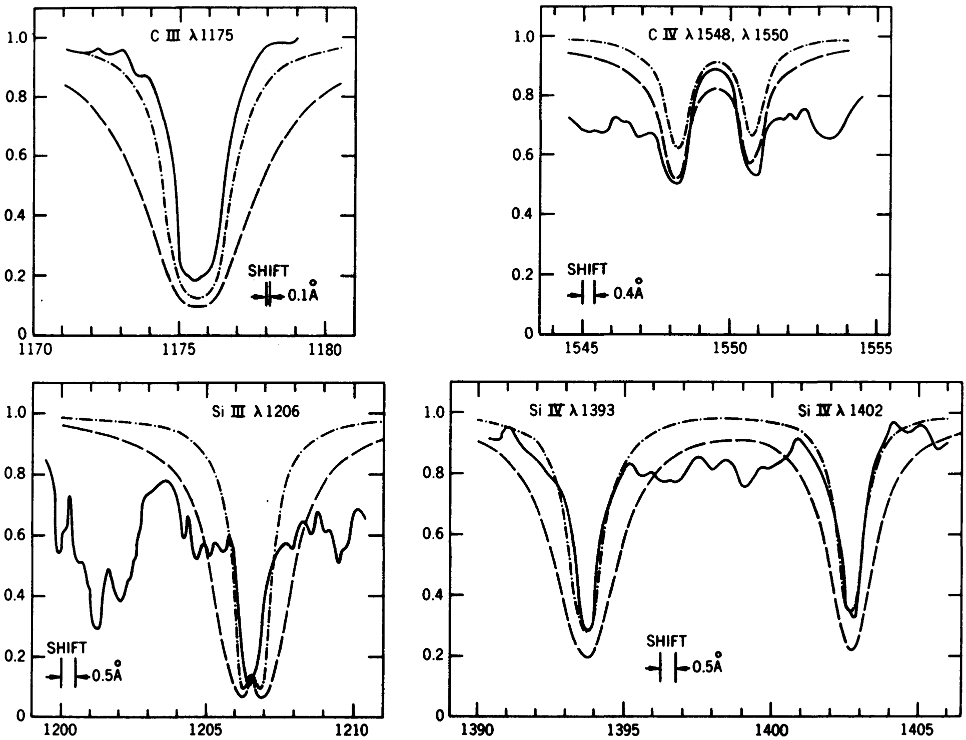

Fig. 2. Observed and Computed Line Profiles in the ultraviolet Spectrum of ζ Tau (Heap, 1975). —— = observed profile, — — = predicted profiles for a normal abundance (C = 8.57, Si = 7.42), —·— predicted profiles for 1/5th normal abundance. All theoretical profiles are based on Mihalas' (1972) model with the parameters, $T_{\text{eff}} = 27\,500$ K, log $g = 4.0$.

120 km s^{-1}. A third surprising feature of the ultraviolet spectrum is the relative sharpness of the stellar lines. The rotational velocity of ζ Tau, as derived from the visual line spectrum, is about 300 km s^{-1} (Underhill, 1952; Slettebak, 1949). However, the computed line profiles in Figure 2 are all artificially rotated to correspond to a projected rotational velocity of only 100 km s^{-1}, and their widths are comparable to the observed line widths. In the case of the C IV doublet, theoretical profiles where $v \sin i = 200$ km s^{-1} tend to blend together, so we know the rotational velocity cannot be that high. Right away, we have found an inconsistency in our picture of ζ Tau. Usually, we assume that a Be star with a *low* projected rotational velocity must be seen pole-on, or near pole-on. We also assume that *shell* stars must be seen equator-on, or near equator-on. The ultraviolet spectrum of ζ Tau indicates both a low projected rotational velocity and a rich shell spectrum. Either the shell around ζ Tau is not so highly concentrated toward the equatorial plane as we had thought, and projection effects are important, or the ultraviolet line spectrum yields a grossly underestimated rotational velocity.

The finding that the effective temperature of ζ Tau is higher than its currently-used spectral type would suggest, is something also found for other Be stars. Panek and Savage (1975) have shown that C IV λ 1550 Å is stronger in the spectra of Be and B-shell stars than in normal B stars of the same spectral type. In most cases, assigning a spectral type to a Be or B-shell star which is one subclass earlier would resolve the discrepancy. Henize *et al.* (1976) have also found that about half of the Be stars observed by Skylab had C IV lines which were abnormally strong for their spectral types. The discovery of blue-shifted photospheric lines in the UV spectrum of ζ Tau is also something which has recently been found in other (but not all) Be stars studied by Snow and Marlborough (1976).

Some space experiments have looked repeatedly at the same object and have thereby provided information concerning the variability of the ultraviolet spectra of Be stars. These data have not been fully assessed as yet, but it is already clear that both the photospheric and shell spectrum of γ Cas is variable. Both Molnar (1975) and Panek and Savage (1975) have reported changes by a factor of two in the strength of the Si IV and C IV resonance lines – lines which are presumably formed in the photosphere of γ Cas. In addition, a comparison of the strengths of the Mg II resonance lines at λ 2800 Å as obtained for γ Cas by different experiments (*cf.* Table II) also reveals changes which are larger than can be explained by systematic errors of the various experiments. Beeckmans (1975) has found that the ultraviolet absolute flux of ζ Tau as measured by TD-1 varies by about ten percent. Because the spectral resolution of the TD-1 experiment is rather low, it is not clear whether this variability is due solely to changes in the shell absorption lines or whether the photospheric spectrum is also variable.

3. Mass Loss

The presence of emission lines in the spectra of Be stars is generally interpreted as evidence for a shell surrounding the star, and the high average rotational velocity is generally interpreted as evidence that rotation plays an important role in forming the shell. One problem with these interpretations has been that the visible spectra of Be stars showed no indications that the stars were actually losing mass or that Be stars were really all rotating at their critical velocities (Slettebak, 1966). There was hope that the ultraviolet spectrum might provide the needed evidence, since it contains the strong resonance lines whose cores are formed at the outermost layers in the atmosphere, perhaps even the interface between the star and shell. These hopes have been fulfilled, at least for the early B-emission stars, with the discovery of three types of anomalous ultraviolet line profiles which may be interpreted as evidence for outward mass motions, perhaps leading to the formation of a shell. First, Bohlin (1970) showed that the C IV resonance doublet in the spectra of γ Cas had P Cygni profiles. The absorption components of each line were displaced shortward by about 450 km s^{-1}. Second, Heap (1975) showed that the strong stellar ultraviolet resonance lines in ζ Tau, although totally in absorption, were all displaced to shorter wavelengths by up to 120 km s^{-1}. Since the visual lines do not show such displacements, she interpreted these net shifts of the ultraviolet lines as evidence for the radial acceleration of material in the photosphere that should lead to mass loss. Finally, Snow and Marlborough (1976) have shown that some Be stars with the earliest spectral types – B0 and B1 – show asymmetrical profiles, with the blueward wings extending to up to 900 km s^{-1}. Some also show the net shifts that Heap found in ζ Tau.

Two notes of caution are appropriate here. One is that there is no evidence for mass loss in the *late*-Be stars, and the other is that there is no proof that the indications of mass loss in the early-Be stars have anything to do with the formation or maintenance of the shell. Certainly, the way in which a shell is formed around a Be star still warrants further investigation.

4. Effects of Rapid Rotation

It is generally believed that the root, underlying cause of the peculiarities of Be spectra is rotation, although its role has not been fully assessed. Various predictions concerning the effects of rapid rotation have been made. These effects include: (1) the alteration of the effective gravity (through the influence of centrifugal force) in such a way as to allow radiation-driven mass loss to occur (Marlborough and Zamir, 1975), (2) the alteration of the continuous and line fluxes due to gravitational darkening, and (3) the alteration of the atmospheric chemical composition in the direction of carbon depletion and nitrogen enhancement (Paczyński, 1971). The Be stars are a very appropriate class of objects to serve as tests to these theories, since as a class they are rapid rotators. It also happens that most of the observable consequences of these theories are most prominent in the ultraviolet region of the spectrum. I will, therefore, review the relevant ultraviolet observations. Since the preceding section dealt with the first effect – mass loss – this section will deal with the second and third predicted effects of rapid rotation.

4.1. Gravitational darkening

Collins (1974a) and others have shown that rapid rotation produces a change in the apparent color temperature of a star and that this change is most obvious in the ultraviolet, where it can amount to a magnitude or more for stars seen equator-on. Using OAO-2 data, Bottemiller (1972) compared the ultraviolet colors of B-shell stars with those of slowly rotating stars, in the belief that shell stars as a class should be rotating near critical velocity and should be seen nearly equator-on. The result of this comparison was that 'if you push eyeball analysis near its limits', you find that shell stars have lower ultraviolet fluxes than normal B stars, which is in accordance with predictions. However, Bless and Code (1972), who also used OAO-2 data, did not find any firm evidence that rapidly rotating stars showed lower ultraviolet fluxes at λ 1700 Å, even though their sample of rapidly rotating stars included Be stars like ϕ Per.

Part of the problem with these comparisons is that the observational scatter amounts to several tenths of a magnitude, which is comparable with the predicted effects of gravitational darkening. There is only one star, ζ Tau, whose absolute ultraviolet flux has been measured by several experiments with high accuracy. This star, which shows a very rich shell spectrum, is a very likely candidate to show the effects of gravitational darkening, and the observations *do*, in fact, suggest that the radiation from this star is strongly affected by gravitational darkening. Figure 3 shows the observed absolute ultraviolet flux of ζ Tau as obtained by Smith (1967),

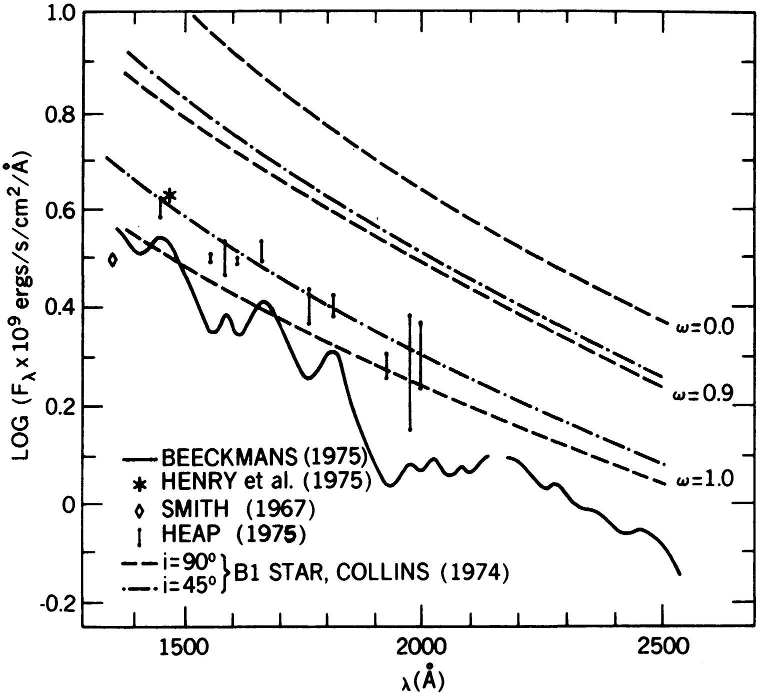

Fig. 3. Ultraviolet Flux of ζ Tau. The observed flux labeled 'Beeckmans' is an eye-estimate of the average of her scans (No. 2, 3, 4 and 5). Collins' theoretical fluxes were scaled such that the visual magnitude corresponds to that of ζ Tau ($V = 2.99$).

the APL group on Apollo-17 (Henry *et al.*, 1975), and by the S2/68 experiment on the satellite, TD-1 (Beeckmans, 1975). The measurements are in substantial agreement with each other. All these fluxes were obtained at low resolution, so they must be corrected for the effects of line-blocking by photospheric and shell lines before comparison with theoretical continuous fluxes can be made. The extent of the line-blocking is considerable (Heap, 1975), and correction for it raises the ultraviolet flux as much as 40% in some regions. However, even when such corrections are made, and allowance for interstellar extinction is made [$E(B-V) \approx 0.01$], the estimated continuous flux of ζ Tau is far below the predicted continuous flux of a non-rotating star. Collins' (1974b) predicted fluxes are shown in Figure 3 for the cases of ω = rotational velocity/critical velocity = 0.0, 0.9, and 1.0, and for angles of inclination of the rotational axis to the line of sight of 45° and 90°. It is evident that the estimated continuous flux of ζ Tau is compatible with a B1-star only if rotating near its critical velocity.

4.2. Alteration of Photospheric Chemical Composition

Paczyński (1971) suggested that for rapidly rotating stars, circulation currents induced by rotation might be sufficient to bring up to the surface material processed by the CNO cycle near the edge of the core. The result of this transfer would be that carbon would be depleted and nitrogen would be enhanced in the photosphere. The extent of the alteration would be most severe for late-B stars, but it would taper off toward earlier spectral types, until at the O stars the alteration would be insignificant.

The ultraviolet region of the spectrum contains strong lines of carbon and nitrogen in varying stages of ionization. Some of the lines most suitable for analysis are: N II λ 1083–5 Å, N III λ 1183, 1184 Å, N V λ 1238 and 1242 Å, N IV λ 1718 Å, C III λ 1175 Å, C II λ 1334–1335 Å, and C IV λ 1548 and 1550 Å. Because of this wide range in ionization, there should be several usable ultraviolet C and N lines for virtually all B-type stars. So far, the only Be star whose ultraviolet spectrum has been analyzed for carbon and nitrogen abundances is ζ Tau. Ionization balance tests, as shown in Figure 2, indicate that carbon is depleted by a factor five below its normal value. However, there is no firm evidence that nitrogen is enhanced in the atmosphere of this star, or the N III λ 1183–1184 Å doublet would appear more strongly than it does. Certainly, the determination of atmospheric abundances in Be stars with the use of strong ultraviolet lines is a promising field worthy of study.

5. Properties of the Shell

It is generally believed that Be stars are a homogeneous group of stars in the sense that they are all main-sequence (or near main-sequence) B-type stars surrounded by shells. Nevertheless, the distinction has sometimes been drawn between Be and B-shell stars: B-shell stars show absorption lines in the visual region of the spectrum, while regular Be stars do not. (Of course, according to this definition, a given Be star might become a B-shell star for a time and then revert back to a Be star.) I do not know if the same generalization holds true in the ultraviolet – that B-shell stars, and only B-shell stars, show shell absorption lines in the ultraviolet region of the spectrum. However, Lamers and Snijders (1975) have shown that Be and B-shell stars *can* be distinguished from one another on the basis of the strength of the resonance lines of Mg II near λ 2800 Å. Figure 4 shows the observed strengths of Mg II as a function of spectral type. The solid line, labeled 'V', represents their mean observed relation for normal main-sequence B-type stars, and the dashed curve shows their mean observed relation for B-type supergiants. The data show that the Mg II lines are weaker in the spectra of Be stars than in the spectra of normal main-sequence B stars, and in a few cases, they are even in emission. However, the Mg II lines have normal or greater-than-normal strengths in the B-shell stars. The one really discrepant case in this figure is ζ Tau. The abnormally strong absorption at λ 2800 Å is undoubtedly due to absorption by Mg II in the circumstellar shell. In fact, enhanced ultraviolet absorption by the shell appears to be the rule for ζ Tau: no ultraviolet emission lines appear in the spectrum of this object.

The visual spectrum of a B-shell star has often been described as appearing composite, with a late-B supergiant spectrum superimposed on an early-B main-sequence spectrum. The same description holds true in the ultraviolet, at least in its gross spectral features. Low-resolution ultraviolet experiments have discovered two features which are characteristic of extended atmospheres: one at λ 1720 Å, first discovered in supergiants by Underhill *et al.* (1972) using OAO-2 spectrometer data;

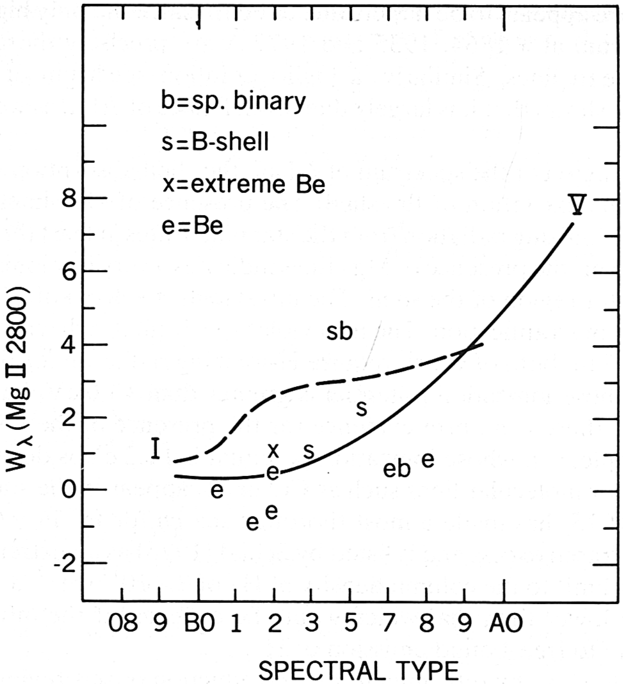

Fig. 4. Equivalent widths for Mg II λ 2800 Å (Lamers and Snijders, 1975).

and another, very broad feature centered on λ 1920 Å, first discovered in supergiants by Thompson *et al.* (1974) using spectrometer data from TD-1. Both of these features are present in the spectrum of ζ Tau, with strengths comparable, or even superseding those of supergiants (Heap, 1975). Figure 5 shows a portion of the λ 1920 Å feature in the spectrum of ζ Tau. The bottom half of the figure shows the actual spectrum of ζ Tau while the top half shows the wavelengths and intensities of Fe III lines as listed by Kelly and Palumbo (1973). As Thompson *et al.* surmised, the

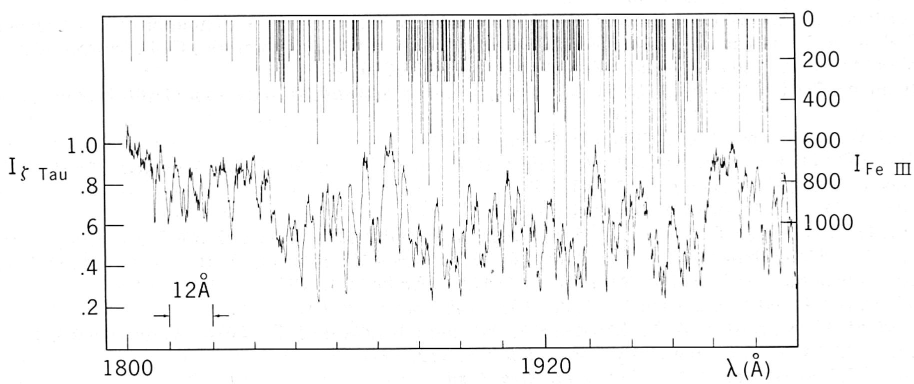

Fig. 5. High-Dispersion Spectrum of the λ 1920 Å feature in the spectrum of ζ Tau (Heap, 1975).

λ 1920 Å feature appears to be largely due to Fe III, since the only high points in the observed spectrum at λ 1864, 1935 and 1972 Å are precisely those places where there are no Fe III lines. Similarly, a high-resolution spectrum of the λ 1720 Å feature in ζ Tau shows that it is largely due to shell lines of Al II, as well as Fe and Ni lines.

In the visual region of the spectrum of ζ Tau, the shell absorption lines indicate a wide range in the excitation of the shell. The presence of He I lines, for example, indicates that H-ionizing radiation from the star penetrates at least the inner layers of the shell. However, the presence of Mg I lines indicates a very low ionization state, no doubt in the outer region of the shell. The ultraviolet spectrum of ζ Tau also shows some indication of stratification. The ultraviolet spectrum is rich with lines from ions like Fe III and Ti III, both of which require H-ionizing radiation for their formation. Ions like Si II whose ionization potential is greater than 13.6 eV, have very strong lines. However, there is no firm evidence for the presence of the lowest excitation lines. For example, C I, whose ionization potential is 11.2 eV is definitely absent.

Neither H^- nor molecular lines such as CO or H_2 appear in the shell spectrum of ζ Tau. Snow (1975) has made a most thorough search for H^- in χ Oph, a Be star which has an infrared excess and is listed by Schild (1973) as an extreme-Be star. He found an upper limit to the column density of H^- of 2×10^{14} cm^{-2}, a value nearly of one magnitude lower than that which would be expected if the infrared excess of χ Oph were due to free-bound emission of H^-.

I would like to close by returning to the introduction of this review and recalling that ultraviolet observations of Be stars are still being obtained and reduced. In these fortunate circumstances, this review can be neither complete nor up-to-date, but I hope that it will provide a starting point for later papers and discussion in this Symposium.

References

Beeckmans, F.: 1975, *Astron. Astrophys.*, in press.
Bless, R. C. and Code, A. D.: 1972, *Ann. Rev. Astron. Astrophys.* **10**, 197.
Bohlin, R.: 1970, *Astrophys. J.* **162**, 571.
Bohlin, R.: 1975, *Astrophys. J.* **200**, 402.
Boksenberg, A., Evans, R. G., Fowler, R. G., Gardner, I. S. K., Houziaux, L., Humphries, C. M., Jamar, C., Macau, D., Macau, J. P., Malaise, D., Monfils, A., Nandy, K., Thompson, G. I., Wilson, R., and Wroe, H.: 1973, *Monthly Notices Roy. Astron. Soc.* **163**, 291.
Bottemiller, R.: 1972, in A. D. Code (ed.), *Symposium on Scientific Results from OAO-2,* Amherst, p. 505.
Burton, W. and Evans, R. G.: 1976, this volume, p. 199.
Code, A. D., Houck, T. E., McNall, J. F., Bless, R. C., and Lillie, C. F.: 1970, *Astrophys. J.* **161**, 377.
Collins, G. W.: 1974a, *Astrophys. J.* **191**, 157.
Collins, G. W.: 1974b, private communication.
Coyne, G.: 1972, in A. D. Code (ed.), *Symposium on Scientific Results from OAO-2,* Amherst, p. 495.
Davis, R. J., Deutschman, W. A., Lundquist, C. A., Nozawa, Y., and Bass, S. B.: 1972, in A. D. Code (ed.), *Symposium on Scientific Results from OAO-2,* Amherst, p. 495.
Delplace, A. M. and Van der Hucht, K. A.: 1976, this volume, p. 197.
Gurzadyan, G. A., Kashin, A. L., Krmoyan, M. N., and Ohanesyan, J. B.: 1974, *Astrofizika* **10**, 177.
Heap, S. R.: 1975, *Phil. Trans. Roy. Soc. London A.* **279**, 371.
Heap, S. R. and Stecher, T. P.: 1974, *Astrophys. J.* **187**, L27.
Henry, R. C., Weinstein, A., Feldman, P. D., Fastie, W. G., and Moos, H. W.: 1975, *Astrophys. J.*, in press.

Henize, K. G., Wray, J. D., Parsons, S. B., and Benedict, G. F.: 1976, this volume, p. 191.
de Jager, C. Hoekstra, R., Van der Hucht, K. A., Kamperman, T. M., Lamers, H. J., Hammerschlag, A., Werner, W., and Emming, J. G.: 1974, *Astrophys. Space Sci.* **26**, 207.
Kelly, R. and Palumbo, L. J.: 1973, *Atomic and Ionic Emission Lines Below 2000 Angstroms*, NRL Report 7599, Naval Research Lab., Washington, D.C.
Kondo, Y., Modisette, J. L., and Wolf, G. W.: 1975, *Astrophys. J.* **199**, 100.
Lamars, H. J. G. L. M. and Snijders, M. A. J.: 1975, *Astron. Astrophys.* **41**, 259.
Lillie, C. F., Bohlin, R. C., Molnar, M. R., Barth, C. A., and Lane, A. L.: 1972, *Science* **175**, 321.
Marlborough, J. M. and Snow, T. P.: 1976, this volume, p. 179.
Marlborough, J. M. and Zamir, M.: 1975, *Astrophys. J.* **195**, 145.
Mihalas, D. M.: 1972, *Non-LTE Model Atmospheres for B and O Stars*, NCAR-TN/STR-76, NCAR, Boulder, Colorado.
Molnar, M. R.: 1975, *Astrophys. J.* **200**, 106.
Paczyński, B.: 1971, *Acta Astron.* **23**, 191.
Panek, R. J. and Savage, B. D.: 1976, *Astrophys. J.*, in press.
Peters, G.: 1976, this volume, p. 209.
Rogerson, J. B., Spitzer, L., Drake, J. F., Dressler, K. Jenkins, E. B., Morton, D. C., and York, D. G.: 1973, *Astrophys. J.* **181**, L97.
Schild, R. 1973: *Astrophys. J.* **179**, 221.
Slettebak, A.: 1949, *Astrophys. J.* **110**, 498.
Slettebak, A.: 1966, *Astrophys. J.* **145**, 126.
Smith, A. M.: 1967, *Astrophys. J.* **147**, 158.
Snow, T. P.: 1975, *Astrophys. J.* **198**, 361.
Thompson, G. I., Humphries, C. M., and Nandy, K.: 1974, *Astrophys. J.* **187**, L81.
Underhill, A. B.: 1952, *Publ. Dominion Astrophys. Obs.* **9**, 139.
Underhill, A. B., Leckrone, D. S., and West, D. K.: 1972, *Astrophys. J.* **171**, 63.
Underhill, A. B. and Van der Hucht, K. A.: 1975, submitted to *Astron. Astrophys.*
Van Duinen, R. J., Aalders, J. W. G., and Wesselius, P. R.: 1973, 'Announcement of Opportunity', Dept. of Space Research, Groningen.
Viotti, R.: 1975, 'Ultraviolet Energy Distribution of the B3e Star HD 200775 in NGC 7023 From TD1-S2/68 Observations', submitted to *Astron. Astrophys.*

DISCUSSION

Bidelman: Were there adequate ground-based observations of ζ Tau at the time that your observations were made?

Heap: Yes. Helmut Abt used the coudé spectrograph of the Kitt Peak 84-in. telescope to get spectra of ζ Tau the night before the rocket launch, and these plates have been a great help, because they allow an estimate of the electron density in the shell (from the Balmer shell lines), an estimate of the surface gravity of the star (from the wings of the photospheric Balmer lines), and things like that.

Swings: (1) I wish to point out that the identification of the λ 1940 absorption feature as Fe III was suggested, and published in 1973, by Swings, Jamar, and Vreux (*Astron. Astrophys.* **29**, 207) in a paper devoted to the reduction of S2/S68 spectrophotometric tracings of B stars. (2) The confirmation came on the basis of *Copernicus* data (note added in proof in the same paper). (3) The strength of the λ 1940 absorption feature is greater in the earlier B stars (earlier than B3); among these λ 1940 is much stronger for the supergiants than for the giants or main sequence stars. A comparison of *Copernicus* data to models and to laboratory intensities of Kelly and Palumbo is given in a paper by Swings, Klutz, Vreux, and Peytremann (*Astron. Astrophys. Suppl.* 1975, in press). (4) I believe it is shown in the paper by Beeckmans that the ultraviolet continuum of ζ Tau between λ 1400 and λ 2500 Å has changed appreciably between 1972 and 1974, both in the slope and in the level in absolute energy of the continuum.

Heap: The variability of the ultraviolet continuous flux of ζ Tau found by Beeckmans is small compared to the ultraviolet deficiency as indicated in Figure 3. I believe that Figure 5 represents the only high-dispersion spectrum of the λ 1920 feature in a Be star obtained so far.

Conti: This talk has been a very nice summary of our knowledge about Be stars derived from ultraviolet data. I am particularly impressed by what appears to be a fundamental difficulty in interpretation. We see evidence of a shell in ζ Tau which is stationary or may even be falling into the star. On the other hand, the same star has an outflowing wind of over 100 km s^{-1}. How can a shell be maintained in the pressure of a wind? Perhaps the wind begins outside the shell, but my impression is that dilution effect arguments, etc.,

https://doi.org/10.1017/S0074180900011323 Published online by Cambridge University Press

always place the shell appreciably away from the star. It seems to me there is a considerable geometric problem in accounting for these observations.

Heap: I agree. There is no guarantee that the mass outflow indicated by the ultraviolet spectra of a Be star has anything to do with the maintenance of its shell.

Hummer: In response to Peter Conti's question, I can imagine two ways in which a reasonably stationary shell can feed a wind flowing from it. (1) If radiation pressure builds up in the shell, say because of recombination, its outer layers could be blown off, while the shell itself remains; (2) a disturbance moving up from below could shock when it reaches a sufficiently low density region, and carry off the outer layers of the shell.

Hutchings; Can I ask about the rotational velocities? You mentioned that in the visual region you get 250 or 300 km s^{-1} while the ultraviolet lines gave you 100 km s^{-1}. Are they the shell lines? Are they also photospheric? Why are they different?

Heap: The lines whose profiles I showed in Figure 2 – Si III λ 1206, Si IV λ 1393, λ 1403, C III λ 1175, C IV λ 1548, λ 1550 – are all *photospheric* lines, and *all* indicate a projected rotational velocity of around 100–150 km s^{-1}. I don't know why the ultraviolet lines suggest a lower rotational velocity than do the visual lines.

Snijders: I should like to comment on the results for the Mg II lines at λ 2800 Å obtained by H. Lamers and me and discussed by you. For some Be stars these lines were observed by many different experiments and comparison of results in various studies shows that the lines are often strongly variable; γ Cas and ζ Tau are good examples. Before 1973 the Mg II lines in γ Cas were far too weak for a B0.5 star. In 1973 they were at least a factor 20 too strong. In ζ Tau the Mg II lines changed by about a factor 2 between 1972 and 1973. If variations of this size occur in other shell lines in ζ Tau they could be responsible for some of the narrow band (35 Å) 'continuum' variations observed by Beeckmans with the S2/68 experiment which were discussed earlier by Swings.