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FIRST ULTRAVIOLET SPECTROPOLARIMETRY OF Be STARS FROM THE WISCONSIN ULTRAVIOLET PHOTO-POLARIMETER EXPERIMENT

K. S. BJORKMAN, K. H. NORDSIECK, A. D. CODE, C. M. ANDERSON, B. L. BABLER, G. C. CLAYTON,[1] A. M. MAGALHÃES,[2] M. R. MEADE, M. A. NOOK,[3] R. E. SCHULTE-LADBECK, M. TAYLOR, AND B. A. WHITNEY[4]
Space Astronomy Laboratory, University of Wisconsin, 1150 University Avenue, Madison, WI 53706
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ABSTRACT

We present the first ultraviolet (UV) spectropolarimetric observations of Be stars. They were obtained with the Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE) aboard the Astro-1 mission. We present WUPPE data on the Be stars ζ Tau and π Aqr, along with near-simultaneous optical data obtained at the Pine Bluff Observatory (PBO). Combined WUPPE and PBO data give polarization as a function of wavelength across a very broad spectral region, from 1400 to 7600 Å. Existing Be star models predicted increasing polarization toward shorter wavelengths in the UV, but this is *not* supported by the WUPPE observations. Instead, the observations show a constant or slightly declining continuum polarization shortward of the Balmer jump, and broad UV polarization dips around 1700 and 1900 Å, which we suggest may be a result of Fe line attenuation effects on the polarized flux. Supporting evidence for this conclusion comes from the optical data, in which we have discovered decreases in polarization across Fe II lines in ζ Tau.

Subject headings: polarization — stars: Be — stars: individual (π Aquarii, ζ Tauri) — ultraviolet: spectra

1. INTRODUCTION

Be stars are rapidly rotating near–main-sequence B stars with optical emission lines. They are highly variable, generally in a nonperiodic fashion, and exhibit several notable characteristics in different wavelength regions: strong and variable UV stellar wind lines (cf. Grady, Bjorkman, & Snow 1987) with variable narrow components (Henrichs et al. 1983; Prinja & Howarth 1986); UV and optical shell lines, indicative of dense circumstellar envelopes (e.g. Oegerle & Polidan 1984); and the presence of "superionized" lines (Lamers & Snow 1978); and excess infrared (IR) emission due to the circumstellar envelopes (Gehrz, Hackwell, & Jones 1974; Waters 1986).

Optical polarization measurements have shown Be stars to be highly polarized (around 1%–2%) (cf. Poeckert, Bastien, & Landstreet 1979). This polarization level, combined with the IR excess, presence of shell lines, and rotation rates near (but not at) break-up velocities, has led to a common view of a dense disklike circumstellar envelope (CSE) around Be stars (Poeckert 1982), possibly with a lower density, high-velocity stellar wind in the polar regions. Because of the disklike geometry, polarization observations provide a useful way of investigating the CSE. This *Letter* reports on the first UV linear polarization measurements of Be stars.

2. OBSERVATIONS

The Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE) is one of three UV telescopes on the Astro-1 payload which flew aboard the space shuttle Columbia in 1990 December. WUPPE is a 0.5 m f/10 Cassegrain telescope and spectropolarimeter; it obtained simultaneous spectra and polarization measurements, with a spectral resolution of about 10 Å, from 1400 to 3200 Å. An equivalent instrument on the 0.9 m telescope at the Pine Bluff Observatory (PBO) was used to obtain near-simultaneous spectropolarimetry from 3200 to 7600 Å. Details about the design of WUPPE can be found in Nordsieck et al. (1992), and the PBO instrument is described in Nordsieck (1992).

A set of Be stars was selected for possible observation with WUPPE on the basis of visibility during the Astro-1 flight plus three other criteria: (1) known moderate-to-high optical polarization; (2) large C IV equivalent widths in the UV (Grady et al. 1987); and (3) a position near the diagonal in the Coté & Waters (1987) diagram of polarization versus IR excess, indicative of a near–equator-on viewing angle. The specific stars observed were a result of real-time decisions made during the flight.

The Be stars observed with WUPPE were π Aqr (two observations of 803 and 1801 s, respectively), ζ Tau (964 s), and PP Car (199 s). The data on PP Car are not included here because of pointing difficulties and a short observation, which resulted in less useful polarization data; we hope to obtain some information after further refinements in the data reduction. Table 1 gives a summary of the observations for ζ Tau and π Aqr.

3. DATA REDUCTION

The data presented in this *Letter* are based on an intermediate calibration; a final version is not as yet available, although most major calibration effects have been accounted for (see Nordsieck et al. 1992). The WUPPE instrumental polarization is about 0.05% and has been removed from the data. We do not expect future improvements in the calibration to change the data significantly, except for possibly the flux calibration and some small wavelength corrections.

After calibration, any interstellar polarization (ISP) must be removed to obtain the intrinsic stellar polarization. However,

[1] Now at Center for Astrophysics and Space Astronomy, Campus Box 391, University of Colorado, Boulder, CO 80309.

[2] On leave from Instituto Astronômico e Geofísico, Universidade de São Paulo, Caixa Postal 9638, SP 01065, Brazil.

[3] Now at Department of Physics and Astronomy, MS-324, St. Cloud State University, 720 4th Avenue South, Cloud, MN 56301.

[4] Now at Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.

TABLE 1

STELLAR PARAMETERS AND OBSERVATIONS

Star	HD Number	Spectral Type[a]	$v \sin i$[a]	WUPPE Observation Date (JD)[b]	WUPPE Aperture	WUPPE Exposure Time (s)	PBO Observation Date (JD)[b]	PBO Exposure Time (s)
ζ Tau	37202	B1 IVe-sh	220	33.9450	6″ × 12″	964	34.7221	11,468
π Aqr	212571	B1 III–IVe	300	31.8867	6″ × 12″	803	25.5117	8192
				35.3821	40″ diameter	1801	35.5042	6553

[a] Spectral types and $v \sin i$ values from Slettebak 1982.

[b] Observation dates are given as JD 2,448,200+ and represent the time of the start of the observation.

removal of the ISP for Be stars can be a difficult problem (McLean & Clarke 1979). Fortunately, in the case of ζ Tau, the ISP is effectively zero (Capps, Coyne, & Dyck 1973; Poeckert & Marlborough 1976), so the observed polarization is intrinsic to the star. For π Aqr, however, the ISP is significant. For this *Letter*, we have assumed an ISP for π Aqr of the form given by a Serkowski law (Serkowski, Mathewson, & Ford 1975), using $K = 0.90$, calculated from the formula of Wilking, Lebofsky, & Rieke (1982), and parameter values from McLean & Clarke (1979), so that the maximum ISP, $P_{max} = 0.36\%$, occurs at a wavelength $\lambda_{max} = 5400$ Å, at a position angle $\theta_i = 120°$.

4. RESULTS

Figures 1 and 2 show the data for ζ Tau and π Aqr before removal of any ISP. Each figure includes three panels showing (*top to bottom*) the flux, the percent polarization (%P), and the position angle (P.A.) of the polarization, as functions of wavelength. The polarization data from the long observation of π Aqr are shown here; there are only small differences between the two observations, and these will be addressed in a later paper. The flux in Figure 2 is from the shorter observation, however, as a good flux calibration for the 40″ diameter aperture is not yet available.

Since there is little ISP in the direction of ζ Tau, Figure 1 gives the intrinsic polarization of ζ Tau. However, for π Aqr we must remove the ISP. Figure 3 shows the intrinsic polarization of π Aqr after removal of the ISP; the flux has been corrected for interstellar reddening using the Cardelli, Clayton, & Mathis (1989) extinction curve with $R_v = 3.2$ and $E(B-V) = 0.23$. Note that a Serkowski law fitted to the ISP may not be good in the UV, as discussed by Clayton et al. (1991); however, given our parameters, we do not expect the uncertainty due to this inaccuracy to be more than ±0.05% in the intrinsic polarization at 2000 Å.

At the time of the Astro-1 mission, ζ Tau was in a high-polarization state, with a large polarization Balmer jump and strong line depolarization effects in the optical. ζ Tau had

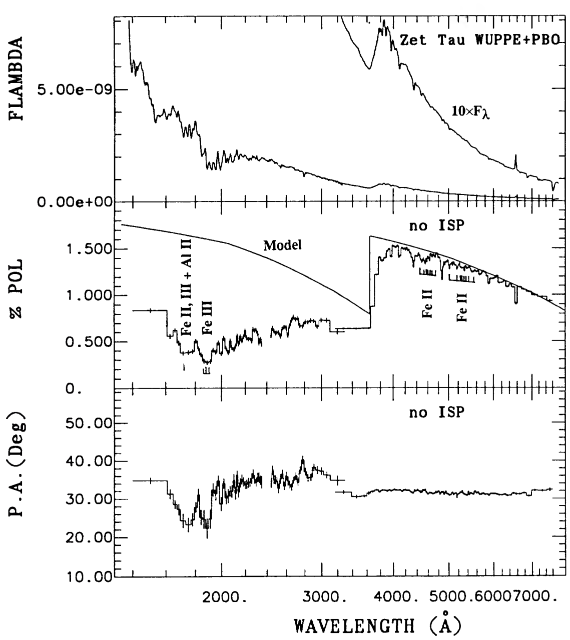

FIG. 1.—Combined WUPPE and PBO data for ζ Tau, showing flux (F_λ, ergs cm^{-2} s^{-1} $Å^{-1}$), % polarization (%P), and position angle (P.A.) vs. wavelength (Å). The %P and P.A. data are binned to a constant error of 0.02% for WUPPE data and 0.01% for PBO data (shown by error bars). The interstellar polarization (ISP) is negligible, so these data represent the intrinsic polarization of the star. The gap near 2400 Å is due to a flaw in one of the detector arrays. Positions of Fe II and Fe III lines are marked with vertical ticks in the second panel (%P). The solid line overplotted on the %P data is a model from Cassinelli et al. (1987—the curve labeled 3.5 in their Fig. 2*a*, with 0.75 sr solid angle), and illustrates predicted wavelength dependence from typical polarization models.

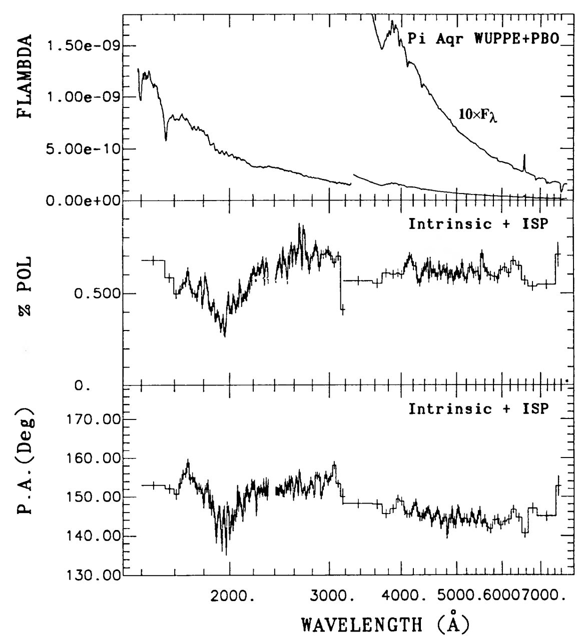

FIG. 2.—Combined WUPPE and PBO data (as in Fig. 1) for π Aqr prior to removal of any ISP. The %P and P.A. data are from the longer observation and have been binned to a constant error of 0.02% for both the WUPPE and PBO data. The UV flux is from the shorter observation of π Aqr, which used the 6″ × 12″ aperture, since a good flux calibration for the 40″ aperture is not yet available. The PBO flux has been normalized to $V = 4.66$, and is rescaled for clarity (as in Fig. 1).

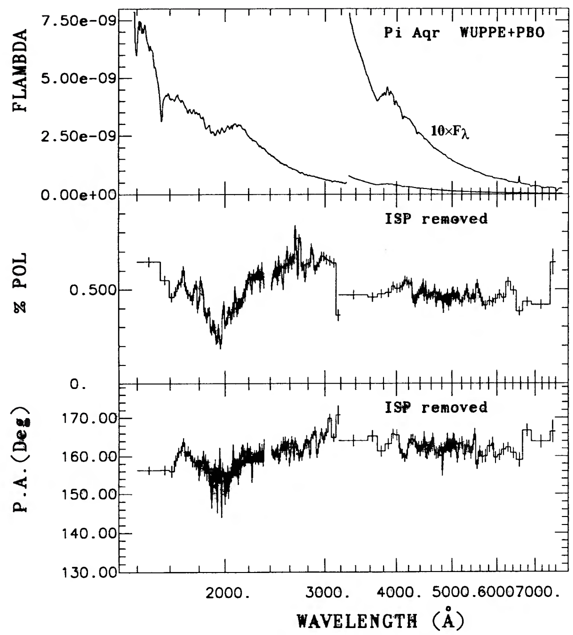

FIG. 3.—The combined WUPPE and PBO data (as in Fig. 1) for π Aqr after removal of a Serkowski law ISP. As in Fig. 2, the data are binned to a constant error of 0.02%, and the flux is from the 6″ × 12″ aperture observation, but here the flux has been corrected for interstellar reddening. Note the lack of a polarization Balmer jump and the presence of UV polarization dips and position angle rotations around 1700 and 1900 Å, similar to that seen in ζ Tau.

shown this level of polarization for the previous 2 years. π Aqr, on the other hand, was in a very low polarization state to which it had declined over the previous 18 months (Bjorkman 1990). The optical data show no polarization Balmer jump in π Aqr at the time of the WUPPE observations.

Several key features of the polarization for ζ Tau and π Aqr are apparent when contrasted with model predictions as in the second panel of Figure 1, which shows the data for ζ Tau and a model prediction from Cassinelli, Nordsieck, & Murison (1987). The particular model shown in Figure 1 was selected to approximate the physical conditions in the disk of ζ Tau. The parameters included (1) a temperature, chosen to match the spectral type; (2) a mass flux, chosen to match the disk density as measured from the size of the polarization Balmer jump and the shape of the polarization Paschen continuum; and (3) a solid angle for the disk, chosen to match the maximum polarization level. Although this model was originally developed for supergiants, the "sawtooth" shape of the wavelength dependence of the polarization is the same as for all models specific to Be stars.

First, note that while the continuum polarization matches fairly well with the model predictions in the optical, the UV polarization disagrees with the models when a large polarization Balmer jump is present. While the models predict rising polarization into the UV, the data actually show constant or slightly declining polarization with decreasing wavelength.

Second, there are strong, broad UV polarization dips around 1700 and 1900 Å, corresponding to the location of numerous iron (Fe) lines in the spectra of both stars (see Fig. 1). Note that the 1700 Å dip is more pronounced in ζ Tau than in π Aqr, which may be an indication of differences in the CSEs of the two stars. Near-simultaneous *IUE* observations confirm the presence of Fe lines in π Aqr (C. A. Grady, private communication); although we could not obtain near-simultaneous *IUE* observations of ζ Tau, the presence of Fe lines in its spectrum is well known (Underhill, Leckrone, & West 1972; Beeckmans 1975; Heap 1977; Snow, Peters, & Mathieu 1979). There is a rotation of the P.A. across the UV polarization dips but not across the polarization Balmer jump. The apparent depolarization across regions of Fe lines also may be seen in P Cygni, one of the hot B supergiants observed with WUPPE (Taylor et al. 1991). The Fe absorption of the flux at 1900 Å has been discussed by Swings et al. (1976).

Third, the optical data show depolarization across the Balmer hydrogen (H) lines, as reported by others (e.g., Poeckert & Marlborough 1977). This has been explained as a dilution effect arising from the emission of unpolarized light from the disk. However, we can now report a new effect: the depolarization of Fe II lines in the optical spectra of ζ Tau (see Fig. 1). Since the Fe lines are weaker than the H lines in the spectrum, the dilution by disk emission in the Fe lines is smaller; hence, the reduction in polarization may be instead an "attenuation" effect arising from the removal of polarized light from the line of sight. More details of this result will be presented elsewhere (Bjorkman et al. 1992a).

5. DISCUSSION

5.1. *Previous Model Predictions*

Typical models of wavelength dependence of polarization in Be stars assume that the polarization is a result of electron scattering of stellar flux within the CSE, reduced by the competing effects of H opacity and dilution by unpolarized emission from the disk. Electron scattering alone produces a polarization spectrum which is flat, but the H bound-free opacity produces the characteristic "sawtooth" shape of standard models (e.g., Poeckert & Marlborough 1978; Cassinelli et al. 1987). All of the current published models assume single scattering and predict that the polarization should rise into the UV (Capps et al. 1973; Poeckert & Marlborough 1978; McLean 1979; Cassinelli et al. 1987; Collins, Truax, & Cranmer 1991), although varying the model parameters can affect the steepness of the rise. Preliminary Monte Carlo models of the polarization produced by optically thick pure H Be star disks also predict rising UV polarization (Whitney & Code 1992). The electron scattering is independent of wavelength, but the H bound-free opacity curve has the same ν^{-3} dependence in both the Paschen and Balmer continua; therefore, if the H bound-free opacity is the dominant absorptive opacity, the shape of the two polarization continua must agree. Since the optical data for ζ Tau show a rapid rise in polarization in the Paschen continuum, the models necessarily would predict a similar rise in the UV (Balmer continuum), which is not observed (see Fig. 1).

5.2. *Implications of the Observations*

The continuum polarization and Balmer jump in the optical are matched quite well by the existing models, demonstrating that the H bound-free opacity is the dominant effect and still must be included in future models. However, since the rise in the UV polarization predicted by H bound-free opacity alone is *not* observed, other effects must offset this rise. Several possibilities are suggested by the UV data. Clearly the metal line opacities in the polarizing region must play a role in UV %P versus λ characteristics. The UV polarization dips around 1700 and 1900 Å correspond to broad absorption features seen in low-resolution UV spectra, which are attributed to the presence of Fe III, Fe II, and Al II around Be and shell stars (Underhill et al. 1972; Swings, Jamar, & Vreux 1973; Vreux, Malaise, & Swings 1973; Thompson, Humphries, & Nandy 1974; Beeckmans 1975; Swings et al. 1976; Heap 1977). This suggests that metal line opacities, and in particular Fe line opacities, must be accounted for in any model for the UV polarization of Be stars.

Other factors may also have to be considered. For example, $\%P$ is a ratio of polarized flux to unpolarized flux; if, with decreasing wavelength, the unpolarized flux rises faster than the polarized flux, $\%P$ will decrease. This can be caused by gravity darkening if the scattered light originates primarily in the equatorial regions of the star. In this case, the polarized light is at a lower brightness temperature than the unpolarized direct light from the polar regions; the contrast can also be enhanced by absorption in the equatorial region near the star. Hence, there can be a decrease in $\%P$ at the shortest wavelengths because there would be more unpolarized light from the hotter polar regions. However, we note that at the shortest wavelengths, the unbinned WUPPE data for ζ Tau show evidence for a rising $\%P$. This wavelength region (around 1400 Å) corresponds to an area where there are few Fe lines present, and so there is less metal line attenuation of the polarized flux. Therefore, before we draw conclusions about the continuum polarization slope, we must be careful to eliminate the effects of line attenuation. Another factor to consider is the physical geometry of the disk, which may cause an increase in the fraction of multiply scattered photons. Some of these effects are being considered in new models under development as part of the analysis of the WUPPE data (Bjorkman & Cassinelli 1992; Taylor & Cassinelli 1992; Whitney & Code 1992).

5.3. *Comparison of the Stars*

According to Slettebak (1982), ζ Tau and π Aqr are of similar spectral type (cf. Table 1), although there has been some debate about the spectral type of ζ Tau (Marlborough 1982). Assuming Slettebak's classifications, a comparison of the two stars, which were in different optical polarization states at the time of the observations, should provide insight into the variable nature of Be star disks. The optical polarization decline of π Aqr in 1989–1990 has been interpreted as evidence of changes in the disk density (Bjorkman et al. 1992b), so the WUPPE observations probe two similar stars in different mass-loss states. The differences in the strength of the UV polarization dip at 1700 Å between the two stars may provide more information about the different states of the CSEs. We will examine these differences in future papers.

The UV polarization dips occur in both ζ Tau and π Aqr, even though the polarization Balmer jump is only present in ζ Tau; therefore, the H and Fe affect the polarization in different ways. With the spectrum of the polarized flux, which can be separated from the overall spectrum, we will be able to sample the disk independently of the combined light from the star plus disk observed in the flux spectrum. This may provide information about the locations of the H and Fe within the disk. Also, since the ratio of Fe II/Fe III is sensitive to temperature, and since the Fe III lines around 1900 Å are metastable (and therefore sensitive to the density; Edlén & Swings 1942), the attenuation of the polarized flux by Fe lines provides a means of probing the temperature and density of the disk material directly.

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