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ULTRAVIOLET SPECTROPOLARIMETRY OF THE Be STAR PP CARINAE WITH THE WISCONSIN ULTRAVIOLET PHOTO-POLARIMETER EXPERIMENT

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ABSTRACT

We present the first ultraviolet spectropolarimetric observations of the Be star PP Car, obtained with the Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE) aboard the Astro 1 mission. Usable polarization data were obtained from 1400 to 2330 Å, along with a good spectrum from 1400 to 3200 Å. These data show a lower polarization shortward of the Balmer jump than had been predicted by standard models, and a broad UV polarization dip around 1900 Å is seen. These results are in agreement with those found from the WUPPE observations of two other Be stars, ζ Tau and π Aqr, which were published earlier. All these observations are an important probe of the Be circumstellar envelopes and demonstrate the need for the inclusion of metal-line effects in circumstellar disk models of Be star UV polarization.

Subject headings: stars: emission line, Be — stars: individual (PP Carinae) — polarization — ultraviolet: stars — circumstellar matter

1. INTRODUCTION

Be stars are rapidly rotating near–main-sequence B stars with emission lines in their optical spectra. Optical polarization measurements have shown Be stars to be highly polarized (around 1%–2%) (see Poeckert, Bastien, & Landstreet 1979). This polarization level, when considered in addition to other known characteristics of Be stars such as IR excess, presence of shell lines, and rapid rotation rates, has argued for a picture of a dense disklike circumstellar envelope (CSE), possibly with a lower density, higher velocity stellar wind in the polar regions (Poeckert 1982). Because of the disklike geometry, polarization observations provide a useful way of investigating the CSE. Prior to the Astro 1 mission, only optical and near-infrared polarization measurements of Be stars had been made. In a previous paper (Bjorkman et al. 1991; hereafter Paper I), we reported on WUPPE observations of two other Be stars, ζ Tau and π Aqr. This paper reports on the first UV linear polarization measurements of the Be star PP Carinae (HD 91465, also known as p Car).

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; the design of the spectropolarimeter permits two orthogonally polarized beams to be recorded simultaneously on a dual (A and B) intensified Reticon array. With this design, WUPPE obtained simultaneous spectra and polarization measurements, with a spectral resolution of about 12 Å, from 1400 to 3200 Å. Details about the instrumentation and design of WUPPE will be discussed in Nordsieck et al. (1993).

Three Be stars were observed with WUPPE during the Astro 1 mission. These stars were π Aqr (two observations of 803 and 1801 s, respectively), ζ Tau (964 s), and PP Car (167 s). The data on PP Car were not included in Paper I because problems with the observation made the data more difficult to reduce. Additional time was also required to refine the data reduction process.

Due to a delayed acquisition of the star, the observation of PP Car was quite short. Also, as an attempt to mitigate the effects of the pointing instabilities encountered during the mission, the largest (40″) aperture of WUPPE was used for the observation. However, there is one position (the "droop" area) within that aperture at which part of the spectrum is projected off the end of the A-array detector. The data in the B-array detector are unaffected in this case, but while one array is adequate for spectral information, the polarization measurements require the data from *both* arrays. In longer observations, the objects were in the droop region only for a small fraction of the total observation time, if at all, so this was not a problem. Unfortunately, PP Car was in the droop area during the entire short observation, resulting in a loss of the polarimetric data longward of 2330 Å. After understanding these problems and carefully refining the data reduction process, we have been able to salvage useful polarimetric results in the region shortward of 2330 Å. Since the data in the B-array were still good longward of 2330 Å, the spectrum is complete from 1400 to 3200 Å. Table 1 gives stellar properties and a summary of the observation for PP Car.

The data presented here have been calibrated using a combination of preflight calibration measurements and in-flight observations of standard stars. The calibration corrects for the effects of thermal background drift, second-order grating contamination, cosmic-ray hits, and telemetry errors; it also accounts for detector flux sensitivity, position angle registration, and polarimetric efficiency (see Nordsieck et al. 1993). The WUPPE instrumental polarization is about 0.05% and

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TABLE 1

STELLAR PARAMETERS AND OBSERVATION INFORMATION

Star	HD Number	Spectral Type[a]	$v \sin i$[a]	Observation Date (JD)[b]	Aperture	Exposure Time (s)
PP Car.........	91465	B4 Ve	250	35.4411	40″ diameter	167

[a] Spectral type and $v \sin i$ value from Slettebak 1982.
[b] Observation date is given as JD 2,448,200 + and represents the start of the observation.

has been removed from the data. The systematic stability of the WUPPE instrument when observing bright stars is 0.04%.

The pointing instability during the observation introduced some errors into the data for which we were able to compensate using a refined data reduction procedure. The total observation was made up of individual 1 s scans of the reticon. Corrections were made for each scan based on the position of the star in the aperture at the time of the scan. This procedure accounted for the scan-to-scan calibration differences introduced by pointing instability. The data from the A-array were unusable longward of 2330 Å because of the droop problem, so the spectrum from 2330 to 3200 Å is comprised of B-array data only. Also, because the observation was so short, only four of the six usual half-wave plate orientations were completed, so the errors reflect this fact.

3. RESULTS

Once the data are calibrated, any interstellar polarization (ISP) contribution must be removed in order to obtain the intrinsic stellar polarization, which serves as a probe of the geometry of the star and the CSE. (For a discussion of ISP in the UV, see Clayton et al. 1992 and Wolff et al. 1993.) However, removal of the ISP for Be stars can be a difficult problem, and estimates of the amount of ISP must usually be made by several different methods (for a discussion, see McLean & Clarke 1979). For this paper, we have adopted the ISP parameter values in the direction of PP Car which were derived by McLean & Clarke (1979) from the combination of measurements of the polarization of nearby field stars and the comparison of continuum and Balmer emission-line polarization in PP Car itself. These techniques give a maximum ISP, $P_{max} = 0.36\%$, which occurs at a wavelength $\lambda_{max} = 5800$ Å, with a position angle $\theta_i = 140°$. These parameters presume that the ISP fits the form given by a Serkowski law (Serkowski, Mathewson, & Ford 1975); the Serkowski law parameter $K = 0.97$, as calculated from the formula of Whittet et al. (1992).

Figure 1 shows the data for PP Car over the wavelength range of WUPPE before removal of any ISP. The figure includes three separate panels showing (from top to bottom) the stellar flux, the percent polarization (%P), and the position angle (P.A.) of the polarization, all as functions of wavelength. Note that the data have been binned to a constant error of 0.058%. These errors reflect the photon-counting statistics; as discussed above, the systematic errors are about 0.04%.

Figure 2 shows the intrinsic polarization of PP Car after removal of the ISP; the flux has been corrected for interstellar reddening using the Cardelli, Clayton, & Mathis (1989) extinction curve with $R_v = 3.2$. The dereddening is based on $E(B-V) = 0.09$, which is derived from $(B-V) = -0.09$ (Stagg 1987) and $(B-V)_0 = -0.18$ (FitzGerald 1970). Note that this is most likely an overestimate of the interstellar reddening, since Be stars are known to have some level of intrinsic reddening due to their CSEs (Doazan 1982). Note also that a Serkowski law fitted to the ISP may not be good in the UV in some cases, as discussed by Clayton et al. (1992) and Wolff et al. (1993); however, given our parameters, we do not expect the uncertainty due to this inaccuracy to be more than $\pm 0.05\%$ in the intrinsic polarization at 2000 Å. Again, as in Figure 1, the WUPPE data are binned to a constant error of 0.058%.

Due to the lack of simultaneous optical polarimetry, we unfortunately cannot say what the optical polarization state of PP Car was at the time of the WUPPE observation. PP Car is known to have highly variable intrinsic optical polarization (cf. McLean & Clarke 1979), much as has been observed in π Aqr (Bjorkman 1992; Bjorkman et al. 1993), so noncontemporaneous observations are of limited use in interpreting the data. However, we do know that at times PP Car has shown a strong polarization Balmer jump in the optical. As an

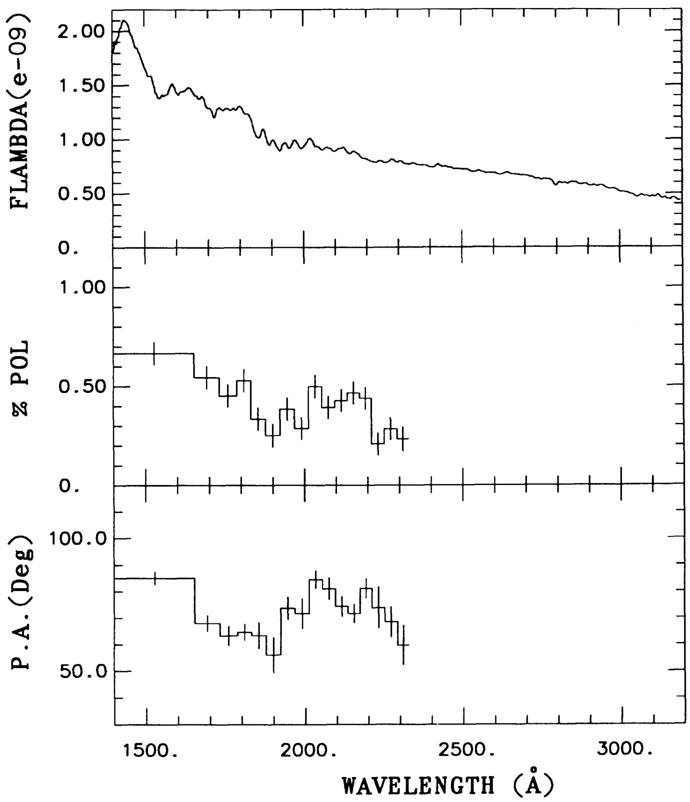

FIG. 1.—The WUPPE data for PP Car, showing flux (F_λ, in units of ergs cm^{-2} s^{-1} Å^{-1}), polarization (%P), and position angle (P.A.) as a function of wavelength (Å). The polarization and position angle data have been binned to a constant error of 0.058% (shown by the error bars). This figure shows the UV polarization dip around 1900 Å and the rotation of the position angle in this region. The missing polarimetric data longward of 2330 Å are due to the observational problems discussed in the text.

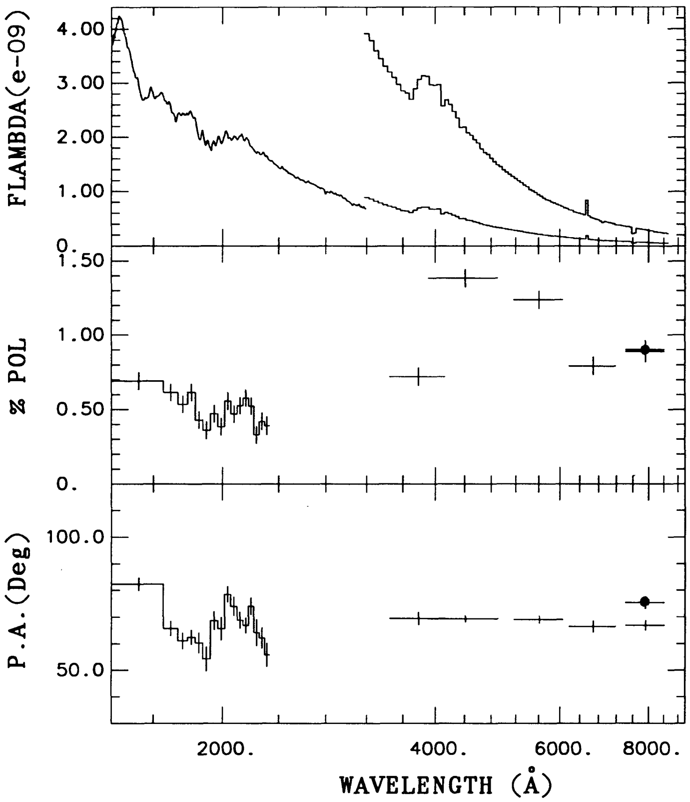

FIG. 2.—WUPPE data (as in Fig. 1) for PP Car after removal of a Serkowski law interstellar polarization. For comparison, we also show some representative optical data from the literature. In the top panel, we include 1981 data taken from Kaiser (1987) to provide an example (although not contemporaneous) of a typical PP Car optical spectrum. The optical flux is also shown scaled up by a factor of 4.4 to more clearly show the spectral features. The fluxes have been dereddened as discussed in the text. In the second and third panels we have included the optical broad-band polarimetric measurements of Serkowski (1970), which were made in 1968, as well as an *I*-band measurement made in 1990 (*dot with error bars*) from Coyne & Minniti (1992), both corrected for ISP. As in Fig. 1, the WUPPE data are binned to a constant error of 0.058%. Note the presence of the UV polarization dip and position angle rotation around 1900 Å, similar to that seen in both ζ Tau and π Aqr (Paper I). The limitations of noncontemporaneous observations are discussed in the text.

example, in Figure 2 we have appended optical broad-band (*UBVRI*) filter polarimetry from Serkowski (1970), which were taken in 1968 when PP Car was in a high polarization state. As an indication of the level of variability, observations of PP Car 1 yr later in 1969, also from Serkowski, showed the polarization to be lower by about a factor of 2 in the *UBV* filters, resulting in a much flatter Balmer jump.

The ISP contribution has been removed from all the polarization data in Figure 2. These data show the large polarization Balmer jump which is typical of Be stars, and which is quite similar to that seen in π Aqr at times when it is in a high polarization state. Also shown in this figure is an *I*-band polarimetric measurement from 1990 May (Coyne & Minniti 1992), which shows a similar value to that found by Serkowski. This is not conclusive, but might suggest that, at least in 1990 May, PP Car may have been in a relatively high polarization state. Note that the *I*-band includes the Paschen jump discontinuity at 8204 Å. In a high polarization state, the measured polarization should be low on the short-wavelength side and higher on the long-wavelength side of this jump, just as it is across the Balmer jump, and thus the *I*-band polarization will reflect an average level across the Paschen jump. For reference, we also show in Figure 2 an optical spectrum from 1981, taken from Kaiser (1987).

Several features are apparent from the WUPPE data, especially when contrasted with model predictions (for a more detailed discussion of the model predictions and how they differ from the observations, see Paper I). First, the models predict an increase in polarization toward shorter wavelengths in the UV, mainly as a result of the spectral (ν^{-3}) behavior of the hydrogen bound-free opacity (see Poeckert & Marlborough 1978; Cassinelli, Nordsieck, & Murison 1987). Our data actually show nearly constant continuum polarization with decreasing wavelength.

Second, there appears to be a broad UV polarization dip around 1900 Å, corresponding to the location of numerous iron (Fe) lines in the spectrum. There is also a rotation of the P.A. across the UV polarization dips. This is consistent with the finding of UV polarization dips in the other two Be stars observed with WUPPE (Paper I), which were attributed to possible attenuation of polarized flux by the disk material. Note that the 1700 Å dip seen in ζ Tau and π Aqr (Paper I) is not as obvious in the PP Car observation. Also, the 1900 Å dip is less pronounced in PP Car than in ζ Tau and π Aqr; in the PP Car data the depolarization is only about 30% of the continuum polarization level, while in the other two stars the depolarization was more like 60% of the continuum polarization level. This could be a manifestation of differences in the nature and physical state of the circumstellar material of the stars. The data on PP Car are not adequate to investigate this possibility in detail. They are more difficult to interpret, because the loss of the polarization data longward of 2330 Å precludes a good definition of the continuum polarization level, and no contemporaneous optical spectropolarimetry is available to help with this problem. We also note that the level of depolarization may be affected by errors in the assumed ISP; however, if the ISP lies within the errors discussed by McLean & Clarke (1979) for PP Car, the uncertainties in the intrinsic polarization shown in Figure 2 are less than $\pm 0.08\%$, and the depolarization is still present at essentially the same level.

4. DISCUSSION

The observation of PP Car supports the conclusions of Paper I, since the UV polarization dips are seen in the same Fe line regions of the spectrum as were noted for ζ Tau and π Aqr. The increasing Fe absorption of the flux at 1900 Å toward earlier spectral types (B5 and earlier) and toward higher luminosity classes has been discussed by Swings et al. (1976); the Fe III absorption multiplets around 1900 to 2000 Å are known to be deeper in earlier B stars (Swings, Jamar, & Vreux 1973). Numerous studies have linked the presence of this absorption feature to the existence of extended circumstellar shells (see Underhill, Leckrone, & West 1972).

PP Car is a later spectral type and lower luminosity class than either ζ Tau or π Aqr, implying that it has a lower temperature and a lower density wind. Also, estimates of the disk densities based on *IRAS* 12 μm data (Waters, Coté, & Lamers 1987, corrected for the spectral types quoted here) indicate that the disk of ζ Tau is approximately 3–4 times more dense than that of PP Car. If this is true, then weaker absorption from the Fe lines in the disk of PP Car might be expected. If the presence of the UV polarization dips is due to attenuation of polarized flux by the material in the disk, as we proposed in Paper I, then weaker Fe absorption from the disk of PP Car would lead to weaker depolarization, which is what is seen in the WUPPE data.

In summary, we suggest that the differences in the magnitude of the depolarization effect between PP Car and ζ Tau or π Aqr are indicative of differences in the density, physical state, and distribution of the circumstellar matter between the three stars. While the PP Car data are not adequate to address these differences in detail, they are a tantalizing indicator that circumstellar densities, as influenced by spectral type, luminosity class, and mass-loss rate, may play an important role in determining the ultraviolet polarization characteristics. This is also supported by the observation of similar Fe line depolarization around 2600 Å in the B supergiant P Cyg (Taylor et al. 1991), which has a much higher mass-loss rate than Be stars. Note that in addition to density effects, the temperatures in the CSE also play a role in determining the polarized flux attenuation, so detailed modeling is required in order to address the relative importance of the density and temperatures. From these considerations, it is clear that differences in UV polarization characteristics provide an important probe of the CSE which is not completely accessible from optical data alone.

We believe that the differences reflected in our data on three stars should be further investigated when WUPPE flies again aboard the Astro 2 mission. In addition, since all three of the Be stars observed with WUPPE on Astro 1 were known shell stars (Bidelman 1976), we suggest for Astro 2 that it would be useful to investigate whether nonshell Be stars show similar UV polarization characteristics. We also note the importance of obtaining contemporaneous optical polarimetric observations, since the presence or absence of a polarization Balmer jump is a critical diagnostic of the disk density.

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REFERENCES

Bidelman, W. P. 1976, in IAU Symp. 70, Be and Shell Stars, ed. A. Slettebak (Dordrecht: Reidel), 457
Bjorkman, K. S. 1992, in Nonisotropic and Variable Outflows in Stars, ed. L. Drissan, C. Leitherer, & A. Nota (ASP Conf. Proc. 22), 71
Bjorkman, K. S., et al. 1991, ApJ, 383, L67 (Paper I)
———. 1993, in preparation
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Cassinelli, J. P., Nordsieck, K. H., & Murison, M. 1987, ApJ, 317, 290
Clayton, G. C., et al. 1992, ApJ, 385, L53
Coyne, G. V., & Minniti, D. 1992, private communication
Doazan, V. 1982, in B Stars With and Without Emission Lines, ed. A. Underhill & V. Doazan (NASA SP-456), 386
FitzGerald, M. P. 1970, A&A, 4, 234
Kaiser, D. 1987, A&AS, 67, 203
McLean, I. S., & Clarke, D. 1979, MNRAS, 186, 245
Nordsieck, K. H., et al. 1993, in preparation
Poeckert, R. 1982, in IAU Symp. 98, Be Stars, ed. M. Jaschek & H.-G. Groth (Dordrecht: Reidel), 453
Poeckert, R., Bastien, P., & Landstreet, J. D. 1979, AJ, 84, 812
Poeckert, R., & Marlborough, J. M. 1978, ApJS, 38, 229
Serkowski, K. 1970, ApJ, 160, 1083
Serkowski, K., Mathewson, D. S., & Ford, V. L. 1975, ApJ, 196, 261
Slettebak, A. 1982, ApJS, 50, 55
Stagg, C. 1987, MNRAS, 227, 213
Swings, J. P., Jamar, C., & Vreux, J. M. 1973, A&A, 29, 207
Swings, J. P., Klutz, M., Vreux, J. M., & Peytremann, E. 1976, A&AS, 25, 193
Taylor, M., et al. 1991, ApJ, 382, L85
Underhill, A. B., Leckrone, D. S., & West, D. K. 1972, ApJ, 171, 63
Waters, L. B. F. M., Coté, J., & Lamers, H. J. G. L. M. 1987, A&A, 185, 206
Whittet, D. C. B., Martin, P. G., Hough, J. H., Rouse, M. F., Bailey, J. A., & Axon, D. J. 1992, ApJ, 386, 562
Wolff, M. J., Clayton, G. C., & Meade, M. R. 1993, ApJ, 403, 722