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FIRST ULTRAVIOLET SPECTROPOLARIMETRY OF HOT SUPERGIANTS

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ABSTRACT

In this *Letter* we present the first UV spectropolarimetric observations of the early-type supergiant stars P Cygni and κ Cassiopeiae obtained with the Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE). Near-simultaneous spectropolarimetric observations of each of these stars were also obtained in the optical region of the spectrum providing complete wavelength coverage from 1400 to 7600 Å. Contrary to model predictions, the intrinsic polarization of P Cyg remains constant in the Balmer continuum except for a broad dip between 2600 and 3000 Å. We discuss this decrease in polarization in terms of possible Fe line blanketing effects. The intrinsic position angle is essentially constant in the UV except for a rotation across the feature between 2600 and 3000 Å. The intrinsic polarization of κ Cas is small; most of the observed polarization is interstellar in nature. We note that the Serkowski curve extrapolated into the UV falls consistently below the observed polarization. Also, a slight rotation in position angle from optical to UV wavelengths is noted. We find very good agreement between the mean continuum polarization obtained by WUPPE and the broad-band UV polarization measurement obtained by Gehrels in 1968.

Subject headings: polarization — stars: atmospheres — stars: individual (P Cygni, κ Cassiopeiae) — stars: supergiants — ultraviolet: spectra

1. INTRODUCTION

Early-type supergiants lose mass at a rate which is surpassed only by the strong winds of Wolf-Rayet stars. Despite intensive UV studies of the atmospheres of these stars, fundamental uncertainties in the mass-loss rates and the mass-ejection mechanisms remain. Ground-based polarization measurements (Hayes 1985; Lupie & Nordsieck 1987; Taylor et al. 1991) suggest that the winds of these stars are likely to be inhomogeneous and asymmetric. This result can significantly change the inferred mass-loss rates, which are based on the assumption of a spherically symmetric ejection of material, as well as our understanding of the mechanisms which drive this mass outward. Theoretical models which make assumptions about the geometry and the physical state of the circumstellar material predict the behavior of the polarization from UV to optical wavelengths (McLean 1979; Cassinelli et al. 1987). In order to fully study the spatial distribution and the nature of this circumstellar material, polarization measurements extending into the UV are necessary. Such data provide us with an opportunity to probe different regions of the stellar atmosphere. In addition, different opacity effects begin to dominate in the UV over those which dominate at longer wavelengths and we can learn more about the nature of the scattering material. The Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE) obtained the first UV spectropolarimetry of the hot supergiants P Cygni, κ Cassiopeiae, and α Camelopardalis. In this *Letter*, we report on preliminary results of the data for P Cygni and κ Cassiopeiae. The WUPPE data for α Cam are presented elsewhere (Clayton et al. 1992).

2. OBSERVATIONS

WUPPE was part of the ASTRO-1 observatory which was flown on board Space Shuttle Columbia in 1990 December. WUPPE is a 0.5 m Cassegrain telescope with a Monk-Gilleson spectrometer. A MgF_2 Wollaston prism is used to split the incident beam into its ordinary and extraordinary components which are detected by a 1024 dual channel reticon. The Stokes Q and U parameters are obtained by alternating half-wave filter pairs on a rotating filter wheel. WUPPE measures polarized light from 1400 to 3200 Å with a spectral resolution of 10 Å. According to a preliminary calibration, the instrumental polarization is ∼0.05%. The programs used to reduce and analyze the data are patterned after routines already written for the reduction of ground-based observations obtained with the 0.9 m Cassegrain telescope at the University of Wisconsin's Pine Bluff Observatory (PBO) (Nordsieck 1991) which is a visible wavelength analog of WUPPE. For a more complete discussion of the WUPPE calibration and data reduction process see Nordsieck et al. (1991).

2.1. *P Cygni*

The WUPPE data for P Cygni were obtained with a $6'' \times 12''$ aperture and a total integration time of 1190 s on 1990 December 5. During this observation, the stability of the instrument pointing system was poor. In the current analysis, we have used only data obtained when the star was well within the aperture; the resulting effective exposure time was 724 s.

In addition to data obtained with WUPPE, ground-based spectropolarimetry of P Cyg was also obtained on 1990 November 29, December 7, and December 11 from PBO. Figure 1*a* shows the flux spectrum from 1400 to 7800 Å; the optical spectrum has been normalized to a V magnitude of 4.9 (AAVSO 1991). Figures 1*b* and 1*c* show the wavelength dependence of the polarization and position angle, respectively, and include all three of the PBO observations. An interstellar

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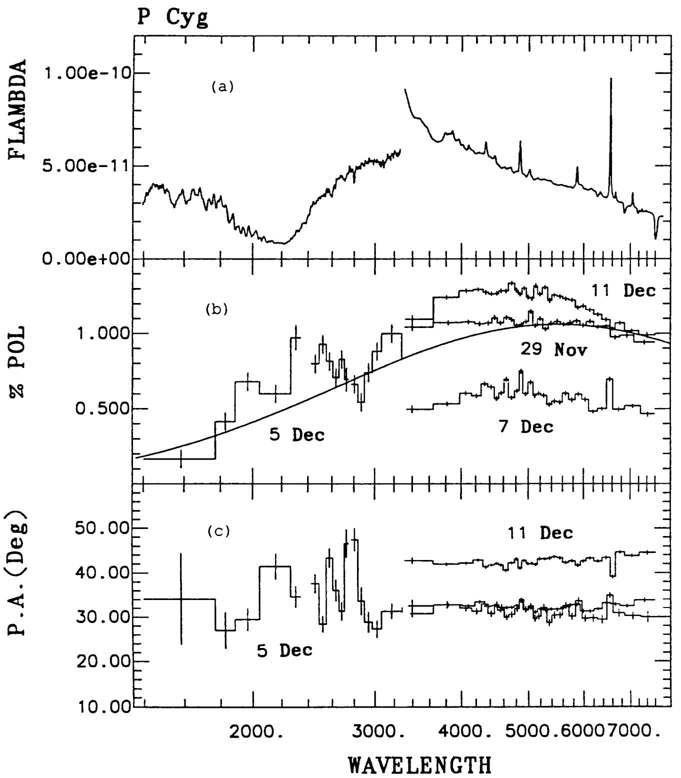

FIG. 1.—The observed WUPPE and PBO data for P Cyg showing (*a*) flux (F_λ, in ergs cm^2 s^{-1} Å, (*b*) percent polarization, and (*c*) position angle, (P.A.) as a function of wavelength (Å). The data are binned to a constant error of 0.06% for the WUPPE data and 0.02% for the PBO data. The curve in (*b*) represents the interstellar polarization based on a Serkowski law. Note the dip in polarization between 2600 and 3000 Å. The gaps in the data around 2400 and 2800 Å are due to a flaw in the cathode of one of the detector arrays.

polarization curve of the form given by Serkowski (Serkowski, Mathewson, & Ford 1975) and modified by Wilking, Lebofsky, & Riecke (1982) is superposed in Figure 1*b*. We have used parameters given by Taylor et al. (1991) which assume that the interstellar polarization has a maximum value, $P_{\max} = 1.06\%$ at a wavelength $\lambda_{\max} = 5500$ Å and at a position angle $\theta_i = 34\overset{\circ}{.}3$ with $K = 0.92$. The polarization data have been binned to a constant error of 0.06% for the WUPPE data and 0.02% for the PBO data. Figures 1*b* and 1*c* clearly depict the temporal variability of P Cyg. Hayes (1985) reports a temporal variation in the continuum polarization, ΔP, of 0.85%. Lupie & Nordsieck (1987) report $\Delta P = 0.46\%$, and Taylor et al. (1991) report $\Delta P = 0.64\%$. The amplitude of the continuum polarization between December 7 and December 11 changed by 0.62% indicating that P Cyg was in a very active polarimetric state during the end of 1990.

Three primary features in the UV polarization data are worth noting: (1) there is a broad dip in the polarization curve between 2600 and 3000 Å; (2) the continuum polarization decreases toward shorter wavelengths which is at least partially due to the fact that the interstellar polarization decreases in the UV; (3) the position angle remains virtually constant at ~34° except for a possible rotation between 2600 and 3000 Å.

2.2. *κ Cassiopeiae*

The WUPPE data for κ Cas were obtained with a 40″ aperture and a total integration time of 1608 s on 1990 December 9. In addition to polarization data at UV wavelengths, we also obtained optical spectropolarimetry from PBO on December 10. These data are shown in Figure 2 in a format similar to that used for Figure 1. Here, the WUPPE data have been binned to a constant error of 0.025% while the PBO data have been binned to 0.015%. In Figure 2*b*, we have also plotted an extrapolated Serkowski curve (Serkowski, Mathewson, & Ford 1975) modified by Wilking, Lebofsky, & Riecke (1982) using $P_{\max} = 1.53\%$, $\lambda_{\max} = 5300$ Å, and $K = 0.89$.

The polarization of κ Cas averaged over the wavelength region spanned by the WUPPE data is 1.096% ± 0.003 while that for the BPO data is 1.436% ± 0.02. The mean position angle of the WUPPE and PBO data are $86\overset{\circ}{.}1 \pm 0.08$ and $85\overset{\circ}{.}2 \pm 0.04$, respectively. The intrinsic polarization of κ Cas is small; Hayes (1984) reports that $\Delta P = 0.38\%$, Lupie & Nordsieck (1987) report $\Delta P = 0.27\%$, and data obtained at PBO between 1989 and 1991 (Taylor 1991) indicate that $\Delta P = 0.17\%$. Clearly, most of the observed polarization is due to the intervening interstellar medium which is consistent with the fact that κ Cas has an $E(B-V) = 0.31$. The Serkowski curve, extrapolated into the UV, falls consistently below the observed polarization. A rotation of the position angle with wavelength has been previously reported for κ Cas (Coyne & Gehrels 1966; Lupie & Nordsieck 1987). We note that the position angle continues to rotate in the UV. It is not yet clear whether this is an intrinsic effect or due to the interstellar medium. κ Cas was one of the highest S/N observations obtained with WUPPE and a detailed analysis of possible small spectropolarimetric features is currently underway.

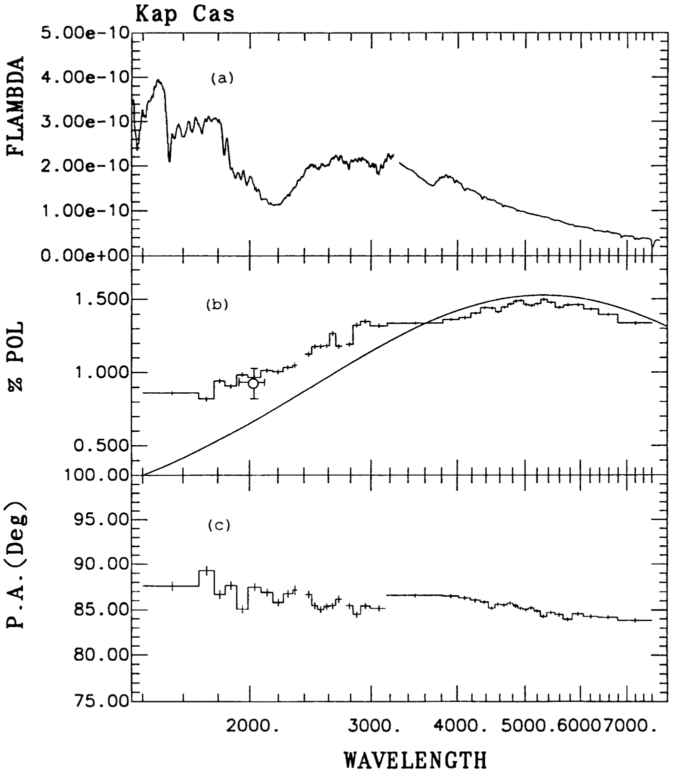

FIG. 2.—The observed WUPPE and PBO data (as for Fig. 1) for κ Cas. The data are binned to a constant error of 0.025% for the WUPPE data and 0.015% for the PBO data. A Serkowski curve is shown in (*b*). The circle in (*b*) represents the polarization measurement by Gehrels in 1968. Note the rotation of the position angle from optical to UV wavelengths.

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Gehrels (1974) measured the polarization of κ Cas through a filter centered at 2274 Å during a balloon launch in 1968. This observation has been plotted in Figure 2*b* with an open circle and accompanying error bars. Gehrels's observation is in very good agreement with the WUPPE data.

3. DATA ANALYSIS

It is the behavior of the intrinsic continuum polarization as a function of wavelength which can be used to probe the geometry and nature of the circumstellar material. Since the observed polarization is a superposition of a wavelength dependent interstellar polarization (Serkowski et al. 1975) and an intrinsic component, it is necessary to determine, and subsequently remove, the interstellar polarization from the data.

In the case of P Cyg, we use the interstellar polarization parameters given by Taylor et al. (1991) and listed above. Figure 3 shows the resulting intrinsic polarization and position angle as a function of wavelength for P Cyg. In addition, we show an error-weighted mean polarization curve obtained from 26 nights of PBO data between 1989 and 1991. The data in this figure have been binned to a constant error, 0.05% for the WUPPE data and 0.005% for the ground-based data. Except for the region between 2600 and 3000 Å, the polarization is constant in the Balmer continuum at ~0.3%. Also, other than a rotation across the feature between 2600 and 3000 Å, the position angle is virtually constant at UV wavelengths.

The observed polarization of κ Cas is comprised of a very strong interstellar component and a comparatively small intrinsic component (~0.1%). In addition, the observed polarization of this star has a maximum at a relatively small wavelength; $\lambda_{\max} \approx 5000$ Å. It may not be valid to extrapolate the Serkowski law into the UV for stars with such a low $\lambda_{\max}$ (Clayton et al. 1991). Therefore, before we can correctly interpret the intrinsic polarization for κ Cas, it is necessary to determine carefully the interstellar polarization law along this line of sight. This research is currently underway and will be discussed in a future paper. In addition, we have been monitoring κ Cas from PBO since 1989. Results of the analysis of these data will be presented elsewhere (Taylor 1991).

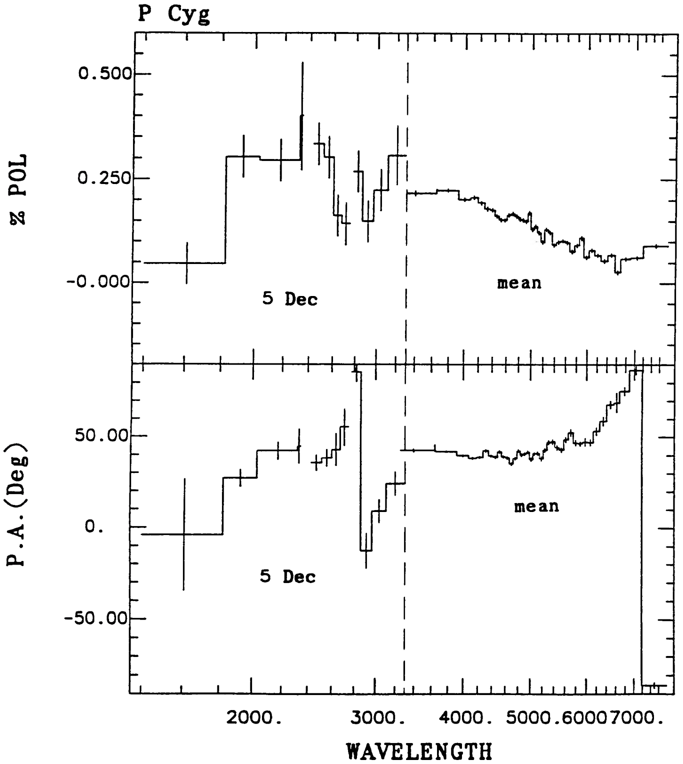

FIG. 3.—The intrinsic polarization and position angle of P Cyg in the UV concatenated with an error-weighted mean polarization and position angle from 26 nights of PBO data. The data are binned to a constant error of 0.05% for the UV data and 0.005% for the visible data. Note the polarization increase from 7600 to 3200 Å, but, the constant polarization in the Balmer continuum except for the region between 2600 and 3000 Å. Note also the rotation in position angle across this feature.

4. DISCUSSION

We have carried out an intensive ground-based program on P Cyg from PBO (Taylor et al. 1991) which supports the idea that the circumstellar wind of P Cyg is inhomogeneous in nature; the amplitude of the continuum polarization and the shape of the polarization versus wavelength curve vary with time as does the intrinsic position angle.

Theoretical models of early-type stars predict a sawtooth behavior of the polarization versus wavelength curve (McLean 1979; Cassinelli et al. 1987); that is, increases in polarization from long to short wavelengths with sharp drops in polarization at the hydrogen series limits. Although we find that the polarization at optical wavelengths can exhibit this type of behavior (Taylor et al. 1991), neither the polarization across the Balmer jump nor the polarization in the Balmer continuum exhibit the behavior predicted by the models. The broad dip in polarization between 2600 and 3000 Å for P Cyg is similar to that which is observed around 2000 Å in the Be stars (Bjorkman et al. 1992). This feature may be due to line blanketing effects near the polarizing region. Numerous Fe II absorption lines have been identified in the P Cyg spectrum between 2300 and 3000 Å (Cassatella et al. 1979) where we see a decrease in polarization. Although Fe III lines have been detected in P Cyg near 2000 Å (Beeckmans 1975), we do not detect a change in the polarization spectrum. Near-simultaneous *IUE* observations show that Fe lines were present in the spectrum of P Cyg at the time of the WUPPE observation (Grady 1990). According to Abbott (1982), line blanketing of the continuum flux can become significant when $\dot{M} > 10^{-6}\ M_{\odot}\ \mathrm{yr}^{-1}$; for P Cyg, $\dot{M} = 1.2 \times 10^{-5}\ M_{\odot}\ \mathrm{yr}^{-1}$ (Pauldrach & Puls 1990). In addition to the high mass loss rate, Swings et al. (1976) report that the intensity of the Fe III lines, at least, is strongest for the most luminous stars; namely, supergiants. Based on these studies, we might have expected to see a change in polarization near 2000 Å as well.

Polarization models for early-type stars generally consider opacity effects only from hydrogen. It seems that for metal-rich stars, opacity effects for other elements, such as Fe, may also play a significant role and should be included in the UV polarization models. Models to explain the polarization data obtained by WUPPE are currently being pursued by Bjorkman & Casinelli (1992), Taylor & Cassinelli (1991), and Whitney & Code (1991).

κ Cas is one of only two stars for which a broad-band polarization measurement had been obtained previously in the UV (Gehrels 1974). Our data fit very well with Gehrels's measurement which was obtained more than 20 years ago. This is an indication that the star is reasonably stable and that most of the observed polarization is interstellar in nature. A detailed analysis and interpretation of the behavior of the intrinsic continuum polarization of κ Cas as well as a study of the small spectropolarimetric features in these high S/N data is pending an accurate determination of the interstellar polarization.

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