1992ApJ...391L..37S

THE ASTROPHYSICAL JOURNAL, 391:L37–L40, 1992 May 20
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THE FIRST LINEAR POLARIZATION SPECTRA OF WOLF-RAYET STARS IN THE ULTRAVIOLET: EZ CANIS MAJORIS AND θ MUSCAE

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Received 1991 November 25; accepted 1991 March 5

ABSTRACT

During the 1990 December Astro-1 space shuttle mission we conducted spectropolarimetry in the wavelength region from 1400 to 3200 Å of the Wolf-Rayet stars EZ CMa (WN5) and θ Mus (WC6 + O9.5I) with the Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE). The UV polarization of EZ CMa displays features which correspond to emission lines. This indicates a large, ~0.8%, intrinsic UV-continuum polarization, and provides further evidence that the wind of EZ CMa is highly distorted. The polarization of θ Mus does not change across emission lines, or the strong interstellar 2200 Å feature. The polarization decreases smoothly to shorter wavelengths, at constant position angle. The combined UV-optical polarization spectrum of θ Mus can be described well with interstellar polarization following a Serkowski law.

Subject headings: polarization — stars: individual (EZ Canis Majoris, θ Muscae) — stars: mass loss — stars: Wolf-Rayet

1. INTRODUCTION

Wolf-Rayet (W-R) stars are hot and luminous stars with extremely strong stellar winds, of order $5 \times 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$ (Willis 1991). We do not as yet fully understand the forces responsible for initiating this high mass loss. It seems that the winds of W-R stars, unlike those of OB stars, cannot be driven by radiation pressure alone. Observations indicate that there is up to 30 times more mechanical momentum in the outflow than there is photon momentum in the radiation field (Willis). A possible means of resolving the momentum problem while keeping with line-driven wind theory is by invoking a secondary mechanism. Poe, Friend, & Cassinelli (1989) propose that W-R stars are luminous, magnetic rotators, with latitude-dependent mass loss. In their model, a fast, purely radiatively driven wind prevails at the poles, while a combination of the line-scattering plus magnetic and rotational forces drives a slow and dense flow from the equator. As a direct observational consequence of axisymmetric mass loss in W-R stars, one expects the radiation to be linearly polarized. Optical spectropolarimetry of W-R stars has been reported by Cohen & Kuhi (1977), McLean et al. (1979), Schmidt (1988), Schulte-Ladbeck et al. (1990, hereafter Paper I), Schulte-Ladbeck et al. (1991, hereafter Paper II), Schulte-Ladbeck et al. (1992c), and Schulte-Ladbeck, Meade, & Hillier (1992a) and supports axisymmetric geometries in two W-R stars, EZ CMa and HD 191765.

UV spectropolarimetry of W-R stars should probe different layers of the atmospheres. According to the standard model (e.g., Hillier 1991), UV continuum radiation originates from denser parts of the stellar wind, and UV emission lines form in different regions than optical lines. A higher signal contrast between the usually small W-R intrinsic and the often large interstellar polarization in the UV was expected, because interstellar foreground polarization had been predicted to decrease in the UV. WUPPE data show this to be true (Clayton et al. 1992).

2. OBSERVATIONS

The two W-R stars observed during the Astro-1 flight, EZ CMa and θ Mus, were selected from a pre-mission list of candidates as a result of real-time scheduling. We gathered 523 s of observing time on EZ CMa, and 288 s on θ Mus, each in a single pointing. The EZ CMa observation was secured on 1990 December 5 (JD 2,448,230.97), in the 6″ × 12″ aperture. It was divided into four sequential subintegrations. The scatter of these four measurements is significantly larger than the error of the individual polarizations, calculated from a least-squares fit to the modulation in three filter pairs (6 σ in the Q parameter). This is probably due to random systematic errors induced by pointing instabilities. The mean (combined) polarization is an error-weighted, pixel-by-pixel average. (WUPPE and its calibration are described in Nordsieck et al. 1992.) The average UV polarization of EZ CMa (excluding an area from 2384 to 2424 Å in which the detector photocathode is flawed) is 0.84% (±0.01%) at a position angle, Θ, of 152°. Optical observations were obtained at Pine Bluff Observatory (cf. Paper II) on 1990 November 29 and 30 and December 7 and 14. The polarization from 3171 to 7581 Å displayed pronounced temporal variability, by $\Delta P = 0.19\%$ (~20 σ), $\Delta\Theta = 8°$, around a mean of 0.539% (±0.007%) at 144°.5. The WUPPE data of θ Mus were collected on 1990 December 4 (JD 2,448,230.42), also in the 6″ × 12″ aperture. The scatter of three subintegrations did not exceed significantly the calculated errors of the individual polarizations. The average UV polarization (excluding detector flaw) is 0.75% (±0.01%) at 79°. Optical spectropolarimetry was gathered at the Anglo-Australian Telescope on 1991 January 29 (JD 2,448,286.24), by Schulte-Ladbeck & Hillier (1992); the polarization measured from 4340 to 5569 Å is 1.523% (±0.003%) at 79°.

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3. EZ CANIS MAJORIS

The UV and optical data are presented in Figure 1. The UV and co-added optical flux spectra meet quite well across the atmospheric cutoff, as do the percentage polarizations, while the position angle spectra display a $\sim 10°$ gap. We attribute this gap to variability (see below).

The following results are independent of the unknown amount of interstellar foreground polarization (hereafter ISP). Polarization changes are detected at the wavelengths of the strongest emission lines, most noteworthy at He II $\lambda 1640$. This is primarily a dilution effect by recombination emission, and it implies that EZ CMa had a substantial, intrinsic UV-continuum polarization at the time of our observation. We detect neither a significant slope of the polarization spectrum in the He II Pickering continuum, nor a change across the He II Fowler jump at 2050 Å. Polarization models for early-type stars generally predict that absorptive opacity should modify the wavelength-independent polarization produced by electron scattering (e.g., Haisch & Cassinelli 1976). WUPPE data hence imply a large electron scattering–to–total opacity ratio, meaning that the region where the polarization is produced is highly ionized. The presence of metal-line opacity due to Fe, discovered with WUPPE to be important in Be stars (Bjorkman et al. 1991) and possibly also in early-type supergiants (Taylor et al. 1991), is not indicated here. There is no suggestion of a systematic change of polarization below 1600 Å, where Fe V and Fe VI lines are known to form a pseudocontinuum in EZ CMa (e.g., Fig. 5 of Schmutz 1991).

Further discussion of the nature of EZ CMa's polarization

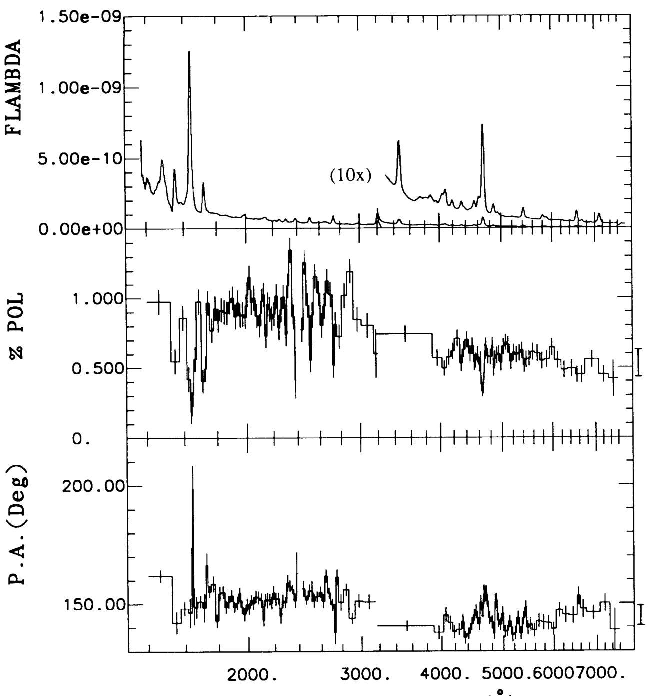

FIG. 1.—Ultraviolet and optical spectropolarimetry of EZ CMa. The units of F_λ are ergs cm^{-2} s^{-1} Å^{-1}. The optical spectrum is overplotted with a magnification of 10. The polarization was binned to constant errors, 0.09% for the UV, 0.06% for the optical data. The optical data represent a mean of four nights. The two bars to the right of the %POL and P.A. plots indicate the range of their variability. The gap in UV coverage near 2400 Å is due to a detector flaw.

requires that the ISP be removed. In Paper II, we determined from EZ CMa data that $P_{\max} = 0.58\%(\pm 0.08\%)$ at $176°(\pm 4°)$, and assumed $\lambda_{\max} = 5600$ Å. The ISP of field stars near EZ CMa (Robert et al. 1991) displays rather chaotic position angles of $155° \pm 13°$; also, the available sightlines are biased to the north of EZ CMa. In order to improve the ISP estimate, we measured the polarization from 3159 to 7599 Å of two stars which Schmutz & Howarth (1991) place close to EZ CMa from an analysis of the interstellar NaD lines: for HD 51854 (B1 V, 1.75 kpc), $P = 0.18\%(\pm 0.04\%)$, $\Theta = 159°(\pm 6°)$; for HD 50562 (B3 III, 1.95 kpc), $P = 0.70\%(\pm 0.04\%)$, $\Theta = 142°(\pm 2°)$. Unfortunately, the above observations indicate a strong spatial variability of ISP toward EZ CMa. We proceed to discuss the data in light of several plausible assumptions. If the ISP is as in Paper II, it is difficult to understand that the observed continuum polarization is so flat. As the ISP declines quickly into the UV, so should the observed polarization. The data could be explained if either the ISP has excess UV polarization over a Serkowski law (possible [see Clayton et al.] but cannot be tested since no UV spectropolarimetry of stars on the sightline to EZ CMa exists), or if the intrinsic polarization both rises and rotates into the UV in such a way that it compensates for the UV color dependence of the ISP (possible, but requires an unlikely balance of two phenomena). Alternatively, there may be no ISP toward EZ CMa, and as a result, we see the flat, electron-scattered spectrum directly. This hypothesis is supported by the apparent lack of a 2200 Å feature in the WUPPE spectrum, and zero polarization in the UV lines (see below). However, our model for the optical polarization would be invalid if this were true (Paper II and below). The flat position-angle spectrum is puzzling also; usually the combination of intrinsic and ISP results in a gradual rotation (unless they are colinear). Even in the absence of ISP, a wavelength dependence of the position angle is expected in a rotationally distorted atmosphere under certain conditions (cf. Cassinelli & Haisch 1974).

There clearly has been variability in the continuum between the UV and visible observations. The optical polarization of EZ CMa is well known to vary (e.g., Drissen et al. 1989). In Paper II, we noticed that the spectrum of the polarization may vary, also. Whereas it is usually flat, it increased into the UV at one epoch and rotated to $\sim 160°$. In Paper II, we explained the rising UV polarization by suggesting the ejection of a high-density plume outside of the plane of the ever-present, axisymmetric wind. This is also a possible interpretation if the intrinsic polarization was increasing in the UV in the WUPPE observation. Firmani et al. (1986) proposed that the variability of EZ CMa, which is periodic in some optical data sets (period = 3.77), is due to a neutron star companion. However, we recently investigated the well-known WN5 + O6 binary V444 Cyg with spectropolarimetry (Schulte-Ladbeck et al. 1992b) and found the continuum–to–He II $\lambda 4686$ line vectors to behave quite differently from those in EZ CMa.

We measured the continuum polarizations in bandpasses which do appear relatively line free, from 1575 to 1597 Å, 1767 to 1949 Å, 2025 to 2091 Å, 2549 to 2695 Å, and 2801 to 3151 Å, and the continuum-free line polarizations in a few of the strongest emission lines, in 30 Å bands. Using the same filters as in Paper II, we also measured the optical polarizations in the co-added spectrum. The results are displayed in Figure 2. All UV lines are consistent with being unpolarized, which might indicate a zero ISP. If the ISP is as in Paper II, He II $\lambda 1640$ still agrees with being unpolarized. Contrariwise, the

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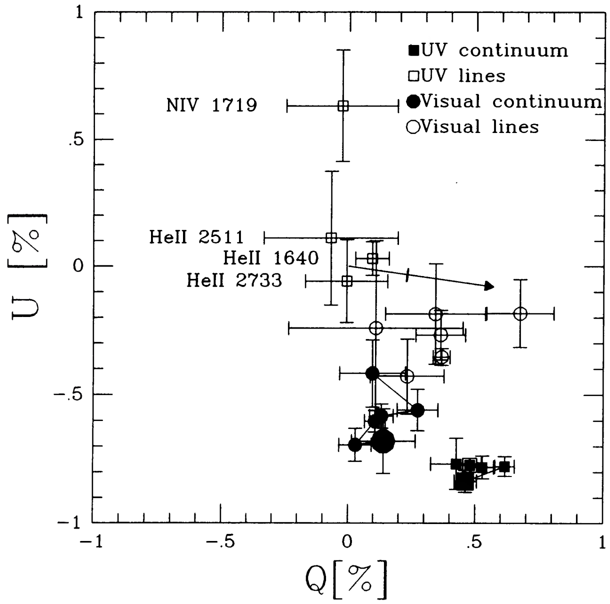

FIG. 2.—The location in the Q-U plane of the polarizations in the UV line-free continuum and continuum-free lines (*filled* and *open squares*) and the optical line-free continuum and continuum-free lines (*filled* and *open circles*). The large circle denotes the polarization in the bluest bin in the visual, while the large square shows the reddest bin in the UV continuum. A vector extending from the origin to a polarization of 0.58% at 176° is our best estimate interstellar vector from Paper II; the fiducial mark indicates its expected amount at 2000 Å, assuming an extrapolated Serkowski law is valid.

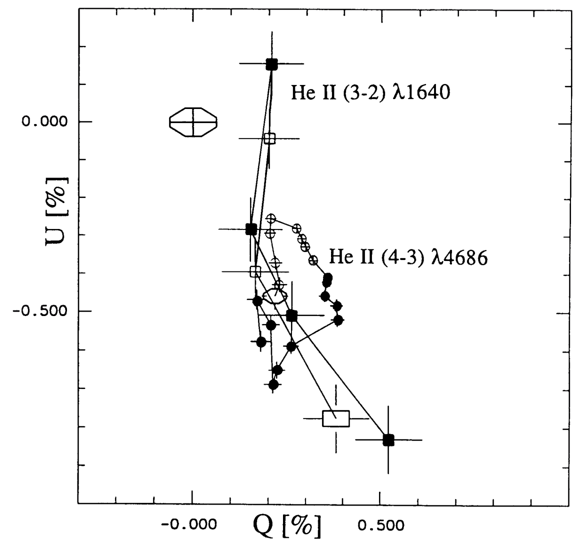

FIG. 3.—*Q-U* diagram of the polarizations across the He II λ1640 (*squares*) and λ4686 (*circles*) lines. The large symbols indicate the bluest points in the line profiles. Open symbols were used for the blue wings of the profiles; filled symbols denote the red wings. The data across the UV line were binned to a constant error of 0.09%. For the optical He II line, we used 16 co-added observations and the data were not binned.

visible lines clearly are polarized in a systematic way. The optical continuum and the optical line polarizations form a band of data points in the direction ∼115°; the continuum-to-line vectors point to the tip of the interstellar polarization vector. This colinear pattern is thought to support an axisymmetric wind geometry, while the polarization differences in various lines relative to the continuum are in qualitative agreement with ionization stratification. However, in the UV, the direction defined by the continuum-to-line vectors is ∼155°. We expected the polarization in N IV λ1719, a line with high ionization potential, to be similar to the UV continuum polarization, which is not the case. The large difference between the polarizations of the He II (6–3) λ2733 and He II (4–3) λ4686 seems odd because of the closeness of their upper levels.

The polarization across He II λ1640 is plotted in Figure 3, overplotted is the polarization across He II λ4686 (using 16 co-added optical observations taken between 1989 and 1991 to increase the S/N). In Paper I, we first observed a loop when the *Q* parameter of the polarization across the He II λ4686 line profile was plotted against the *U* parameter. He II λ1640 apparently did not display a *Q-U* loop in the WUPPE observation. However, it is not described by a linear drop from and recovery to the continuum polarization either; there is a difference in direction between the line wings, ∼155°, and line center. The blue wing of He II λ4686 extends in the same direction as the He II λ1640 wings, but then rotates toward line center to the direction of the optical continuum-to-line vectors, ∼115°, while the red wing points in the opposite direction from the blue wing. If loops are caused by expansion and rotation (cf. Poeckert & Marlborough 1978), and if the stratified winds of W-R stars rotate differently, then the absence of a loop in He II λ1640 implies that it is formed farther out in the wind than He II λ4686, contrary to the structure of the standard model (Hillier 1987). Alternatively, since optical observations of higher resolution (Schulte-Ladbeck & Hillier 1992) indicate that the loop width of He II λ4686 varies as a function of time, it may be possible that the He II λ1640 loop width is time dependent, also, and that it was small at the time of the WUPPE observation. This phenomenon may perhaps be attributed to variations in the radius at which lines form, perhaps caused by variations in the mass-loss rate. One might also expect self-absorption of line photons to be important; combined with the effects of Doppler shifts, this results in a dependence of the effective scattering geometry of the lines on the wind dynamics.

In summary, the first UV spectropolarimetry of EZ CMa exhibits many surprising characteristics, which should put new constraints on any model for its extended atmosphere. The continuum polarization does not show spectral variations due to bound-free He opacity, or rotation of the plane of polarization, or a change in polarization in the red portion of the Fe pseudocontinuum. While the absolute amount of UV continuum polarization remains uncertain due to the unknown ISP, a large, ∼0.8%, polarization is inferred by using either the UV recombination lines or the extrapolated ISP derived in Paper II as a zero point, thus requiring considerable asphericity. Details of the line polarizations, as well as the overall UV-optical polarization spectrum remain unexplained. Additional and more simultaneous UV-optical data are needed to resolve the possible interpretations. Future polarimetry of W-R stars shortward of 1600 Å might also be of interest, to further study the Fe pseudocontinuum, as well as the resonance lines.

4. θ MUSCAE

Spectropolarimetry of θ Mus spanning the UV-optical range is shown in Figure 4. The polarization of θ Mus does not change across emission lines. There is no change of polarization associated with the interstellar 2200 Å bump. The amount of polarization drops steadily toward shorter wavelengths, while the position angle remains constant.

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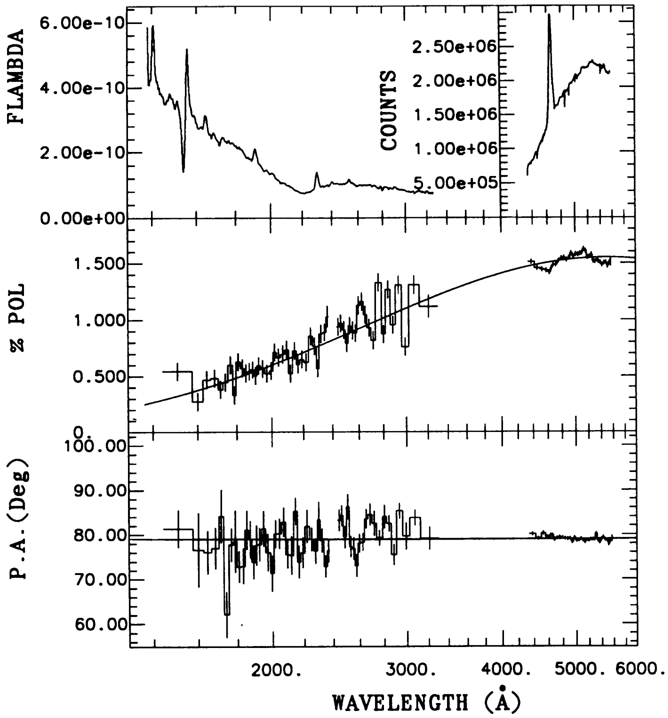

FIG. 4.—UV-optical spectropolarimetry of θ Mus. The optical spectrum is displayed in counts. The polarizations were binned to an error of 0.08% in the UV, and 0.02% in the optical. There are two gaps in the coverage, near 2400 Å due to the detector flaw, and between 3200 and 4200 Å due to incomplete instrumental coverage. The solid lines represent a fit with a Serkowski law for interstellar polarization. Apparent features in the optical polarization are due to a wavelength-dependent systematic error in the calibration.

In Figure 4, we display a fit with a Serkowksi law with parameters $P_{\max} = 1.55\%$, $\lambda_{\max} = 5500$ Å at $\Theta = 79°$. WUPPE data show that an extrapolated Serkowski law provides a good fit to several sightlines (Clayton et al.). It is an excellent model for the θ Mus observation and implies a rather normal line of sight, with $R_V = 3.1$ and $E_{B-V} \geq 0.17$.

Evidence for intrinsic polarization in θ Mus comes from its variability. St.-Louis et al. (1987) detected 0.2% variations around a mean of 1.45% at 82° in a blue filter centered at 4700 Å (FWHM 1800 Å). Polarimetry in U to I by Coyne & Minniti (1990) on 1990 May 21 and 22 gives values close to these. St.-Louis et al. describe the variations as intrinsically noisy without the convincing double-wave phase modulation expected from binarity (period = $18^{d}341$), and speculate that they might originate from wind inhomogeneities in the O9.5 supergiant companion. They give the mean polarization of 50 stars within a 4° circle around θ Mus as 1.986% at $78°6$.

Our data were taken at phases 0.59 (UV) and 0.63 (optical), when the W-R star was located behind the O star. If there had been intrinsic polarization at the 0.2% level at the time of our UV observation, and if it had had a position angle other than the interstellar one, we should have been able to discriminate it against ISP at the short end of the UV spectrum. We are led to the conclusion that the intrinsic polarization of the θ Mus system is sometimes not easily distinguished from ISP with spectropolarimetry.

We thank the people who have worked on the Astro-1 mission, the ground-based observers who kept monitoring our objects, especially G. V. Coyne and D. Minniti, C. Grady for obtaining near-simultaneous *IUE* data, the staff of the AAT for assistance with the observations, the Simbad data center from which we retrieved bibliographical information, and the NSSDCA for providing us with *IUE* data. This work was supported by NASA contract NAS5-26777.

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