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POLARIZATION VARIABILITY AMONG WOLF-RAYET STARS. VI. LINEAR POLARIMETRY OF THE ECLIPSING BINARY V444 CYGNI

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ABSTRACT

We report precision broad-band blue light monitoring in linear polarization of the bright Cygnus W-R + O system V444 Cyg. Analysis of the data yields an orbital inclination $i = 78\overset{\circ}{.}5$, in good agreement with previous estimates based on polarimetry and on the analysis of light curves. In addition, V444 Cyg shows rapid polarimetric modulation around phase 0.5, when the O star companion eclipses the scattering electrons located primarily in the dense inner W-R wind (as predicted years ago by Chandrasekhar for early-type stars in general). Simple modeling of the polarization eclipse based on a spherical electron envelope around the W-R star yields a satisfactory fit to the data. This model also supports the small value of the W-R core radius (2.9 $R_{\odot}$) previously proposed by other authors.

Subject headings: polarization — stars: eclipsing binaries — stars: individual (V444 Cyg) — stars: Wolf-Rayet

I. INTRODUCTION

V444 Cyg (HD 193576) is a spectroscopic binary (WN5 + O6) which exhibits deep eclipses. Therefore, it offers an exceptional opportunity to study the geometrical structure of a Wolf-Rayet (W-R) star. For example, the detailed analysis of IR to UV light curves by Cherepashchuk, Eaton and Khaliullin (1984, hereafter CEK) yields a maximum radius of the W-R core $R_{\text{W-R core}} = 2.9\ R_{\odot}$, a minimum effective temperature $T_{\text{eff}} \simeq 90{,}000$ K, and an empirical trend for the radial dependence of the electron density in the wind.

Kron and Gordon (1950) described the W-R component in V444 Cyg as a small, hot object buried in a strongly ionized envelope. An earlier study by Hiltner (1949) had already pointed out the existence of an extended electron envelope around the W-R star. These free electrons are the primary cause, via Thomson scattering, of the polarization observed in the binary V444 Cyg. Polarimetric data are very useful, if not essential in some cases, to determine the orbital inclination of a binary system. In the case of V444 Cyg, an orbital inclination around 78° was first deduced from the light curves (Kron and Gordon 1950; see also Cherepashchuk 1975). Polarimetric studies so far have revealed an orbital inclination of ~80° (Hiltner and Mook 1966, hereafter HM; Rudy and Kemp 1978, hereafter RK; and more recently, Piirola and Linnaluoto 1988, hereafter PL). Here we recalculate the orbital inclination taking into account effects neglected in the previous polarimetric work. These effects include the eclipse of the W-R wind scatterers, the eclipse of the light sources, and the interstellar component of polarization.

In the last part of this paper, we construct a simple model for the eclipse of the electrons in the W-R wind by the O star around orbital phase 0.5. This phenomenon was first predicted by Chandrasekhar (1946) for early-type stars without winds. It was looked for by Hiltner (1949) in a few W-R binaries without success. The eclipse is clearly seen in the present work probably because of the higher orbital inclination of V444 Cyg but also because of the higher precision obtained.

Details concerning the data acquisition and reduction are given by Robert *et al.* (1989, hereafter Paper V), who discuss the polarimetric observations of the other bright W-R stars in Cygnus.

II. PRELIMINARY ANALYSIS AND COMPARISON WITH PREVIOUS POLARIMETRIC RESULTS

The normalized Stokes parameters Q and U observed here are presented in Table 1 and plotted versus the orbital phase, φ, in Figure 1*a*. The phases were calculated from the most recently estimated period $P = 4.212435$ days and origin of phases at JD 2,441,164.337 (primary light minimum, when the W-R star is in front) deduced by Kornilov and Cherepashchuk (1979). The solid curves through the data in Figure 1*a* are the result of a Fourier fit with the following terms:

$$Q = q_0 - q_1 \cos \lambda + q_2 \sin \lambda + q_3 \cos 2\lambda + q_4 \sin 2\lambda ,$$
$$U = u_0 + u_1 \cos \lambda + u_2 \sin \lambda + u_3 \cos 2\lambda + u_4 \sin 2\lambda , \quad (1)$$

where $\lambda = 2\pi\varphi$. The fitted values of the coefficients q_i and u_i yield ellipses in the Q-U plane, traced out twice per orbit (Fig. 1*b*).

According to the equations of Brown, McLean and Emslie (1978, hereafter BME), revised by Drissen *et al.* (1986*a*), the coefficients of the fit give, among other parameters, an orbital inclination $i = 79\overset{\circ}{.}9 \pm 0\overset{\circ}{.}5$ and an angle between the major axis of the ellipse in the $Q-U$ plane and the Q axis (taken parallel to the celestial North Pole) $\Omega = 318\overset{\circ}{.}1 \pm 0\overset{\circ}{.}9$. (The uncertainties in i and Ω are calculated according to the formal method of propagating errors. The method of Aspin, Simmons, and Brown 1981, based on the optimum fit to the data, would lead to an error of $\pm 2°$ in i, within a 90% confidence interval.) HM obtained, from their polarimetric observations in nonfiltered light, an inclination of 76° ± 6°. (The analysis of these data repeated here with the equations of BME gives $i = 83\overset{\circ}{.}2 \pm 4\overset{\circ}{.}3$ and $\Omega = 319\overset{\circ}{.}6 \pm 8\overset{\circ}{.}3$.) The more recent polarimetric data of RK in a standard B filter, yield an orbital inclination of $76\overset{\circ}{.}0 \pm 2\overset{\circ}{.}3$ (our analysis according to the equations of BME). The angle Ω is not calculated in the case of HM because of an ambiguity in the origin of the position angle; this does not affect i. Also, PL obtained $i = 82\overset{\circ}{.}8 \pm 0\overset{\circ}{.}9$ and $\Omega = 316° \pm 1°$

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TABLE 1

LINEAR POLARIZATION DATA FOR V444 CYGNI

Julian Date (2,400,000+)	P (%)	σ_p (%)	θ	σ_θ	Q (%)	U (%)	φ[a]	Source[b]
46362.787	0.271	0.009	138.5	0.8	0.033	−0.269	0.072	1
46363.679	0.585	0.010	147.7	0.5	0.251	−0.528	0.284	1
46363.764	0.567	0.012	151.6	0.6	0.310	−0.474	0.304	1
46364.604	0.367	0.006	142.3	0.5	0.093	−0.355	0.504	1
46364.769	0.235	0.012	162.0	1.4	0.190	−0.138	0.543	1
46365.746	0.577	0.008	152.0	0.4	0.323	−0.478	0.775	1
46366.637	0.280	0.009	142.0	0.9	0.068	−0.272	0.986	1
46366.776	0.227	0.010	151.1	1.2	0.121	−0.192	0.019	1
46367.728	0.626	0.010	151.9	0.5	0.348	−0.520	0.245	1
46369.775	0.574	0.011	149.6	0.5	0.280	−0.501	0.731	1
46371.689	0.522	0.008	144.9	0.4	0.177	−0.491	0.186	1
46704.885	0.604	0.024	155.9	1.1	0.403	−0.450	0.284	2
46707.672	0.266	0.017	145.6	1.8	0.096	−0.248	0.946	2
46708.620	0.539	0.014	147.5	0.7	0.228	−0.488	0.171	2
46710.612	0.518	0.015	144.6	0.8	0.170	−0.489	0.643	2
46711.843	0.288	0.015	148.0	1.4	0.126	−0.259	0.936	2
46712.673	0.374	0.013	143.3	1.0	0.107	−0.358	0.133	2
46716.702	0.339	0.014	135.7	1.1	0.008	−0.339	0.089	2
46718.620	0.178	0.014	156.4	2.2	0.121	−0.131	0.544	2
46720.596	0.323	0.010	141.3	0.9	0.070	−0.315	0.014	2
46720.767	0.300	0.011	140.2	1.0	0.054	−0.295	0.054	2
46721.628	0.565	0.012	151.8	0.6	0.313	−0.471	0.259	2
46721.757	0.547	0.007	152.9	0.4	0.320	−0.444	0.289	2
46722.634	0.418	0.011	139.2	0.7	0.061	−0.414	0.497	2
46723.640	0.651	0.011	149.1	0.5	0.308	−0.574	0.736	2
46723.775	0.592	0.012	150.9	0.6	0.312	−0.503	0.768	2
46724.622	0.267	0.011	140.4	1.1	0.050	−0.262	0.969	2
46724.751	0.233	0.010	138.9	1.2	0.032	−0.231	0.000	2
46725.625	0.554	0.011	149.2	0.6	0.263	−0.487	0.207	2
46726.697	0.295	0.009	131.4	0.9	−0.037	−0.293	0.462	2
46727.672	0.563	0.012	148.2	0.5	0.250	−0.504	0.693	2
46728.587	0.292	0.010	151.2	1.0	0.156	−0.247	0.911	2
46728.710	0.283	0.010	142.4	1.0	0.072	−0.274	0.940	2
46729.675	0.477	0.009	145.2	0.5	0.166	−0.447	0.169	2
46730.611	0.321	0.010	154.1	0.9	0.199	−0.252	0.391	2
46731.777	0.522	0.011	145.7	0.6	0.190	−0.486	0.668	2
46732.608	0.423	0.011	154.8	0.7	0.270	−0.326	0.865	2
46733.640	0.394	0.008	140.5	0.6	0.075	−0.387	0.110	2
46733.771	0.456	0.011	141.7	0.7	0.106	−0.444	0.141	2
46734.603	0.512	0.010	153.5	0.6	0.308	−0.409	0.339	2
46734.711	0.457	0.009	153.0	0.6	0.269	−0.370	0.364	2
46735.591	0.267	0.015	143.1	1.6	0.074	−0.256	0.573	2

[a] φ is calculated with $P = 4.212435$ days and $E_0 =$ JD 2,441,164.337 from Kornilov and Cherepashchuk 1979.

[b] SOURCES.—(1) 1985, Mount Lemmon and Mount Bigelow; (2) 1986, Mount Lemmon.

from their polarimetric data of 1981 and 1982 in standard broad-band blue light. We conclude that, within their estimated errors, i and Ω have not changed over the 20 yr time base. These two parameters are determined again in § III, where we take into account important effects not considered in the model of BME.

The amplitude of the polarimetric variations, A_p, is taken to be the length of the semimajor axis of the ellipse in the $Q-U$ plane. Combined with other parameters, A_p yields a measure of the mass-loss rate $\dot{M}$ for the W-R component (see St.-Louis *et al.* 1988, hereafter Paper III). The estimated values for A_p range from 0.232% ± 0.049% for HM to 0.175% ± 0.016% for our data (with intermediate values for RK and PL). Therefore, $\dot{M}$ of the WN5 component in V444 Cyg has probably remained constant to within the observational uncertainty of about ±15% over the last 20 yr.

The symmetric shape of the Fourier fit (associated with the fact that the second harmonic coefficients are much greater than the first harmonic coefficients) strongly suggests that, for all intents and purposes, the electron envelope is corotating and is distributed symmetrically about the orbital plane. According to the procedure of BME, we calculate $A = G/H = 12$ (where H is the effective concentration of material within the orbital plane and G is the effective degree of asymmetry about the orbital plane; e.g., $G \rightarrow 0$ for a completely symmetric envelope). The relatively high value of A obtained, as also seen for other W-R binaries (see Bastien 1988), suggests that we are dealing essentially with a symmetric envelope.

The superior precision of the present data for V444 Cyg clearly allows one to see for the first time in a W-R star a phenomenon predicted years ago by Chandrasekhar (1946). He showed that a nonzero polarization should be detectable as a result of the eclipse by a companion star of the scatterers surrounding a radiating star. In the case of V444 Cyg, the radiation of the W-R star is scattered by the electrons in its own wind, while the O star acts as the occulting body. The resulting

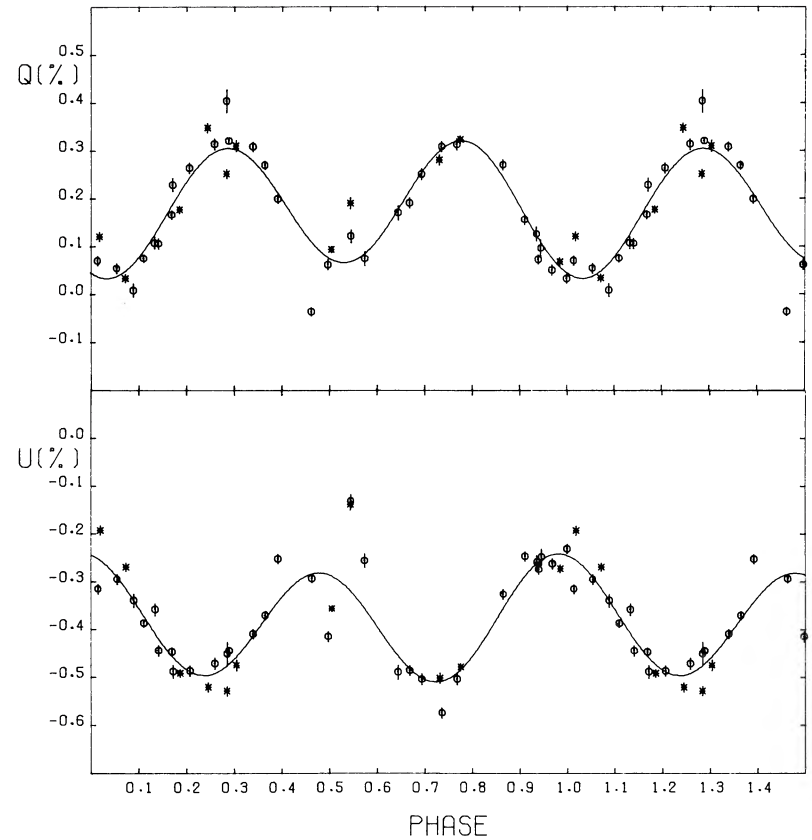

FIG. 1*a*

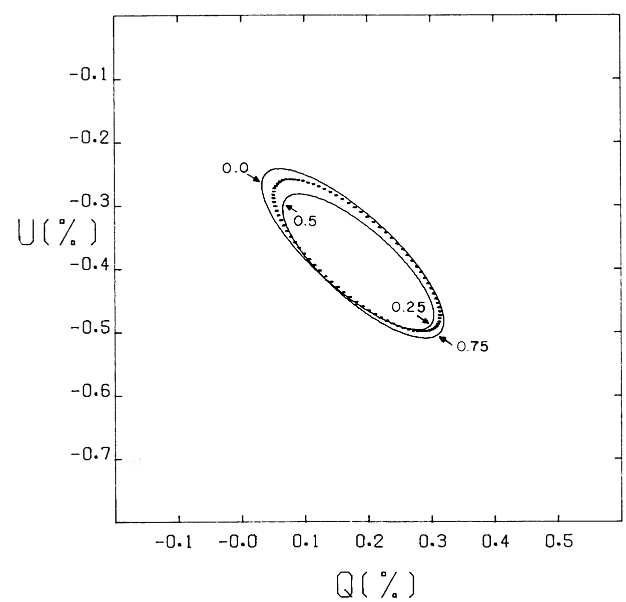

FIG. 1*b*

FIG. 1.—(*a*) Stokes parameters Q and U for V444 Cyg vs. orbital phase. The phase is calculated with the ephemeris of Kornilov and Cherepashchuk (1979): JD 2,441,164.337 + 4.212435(*d*) × E (primary light minimum with W-R star in front). Stars and circles refer to the measurements from 1985 and 1986, respectively. Vertical bars are 2 σ error estimates, where σ is taken to be purely due to photon statistics. Solid curves correspond to the best fit of a Fourier series up to second-harmonic terms. (*b*) Polarimetric variations for V444 Cyg in the $Q-U$ plane. Solid curves correspond to the fit for Fourier series in Fig. 1*a*. The dotted curve refers to the averaged $Q-U$ locus. Phase are indicated along the curves.

phase-dependent modulation in polarization, which increases dramatically around phases 0.5 ± 0.1, is superposed on the slower, double-wave binary modulation (see Fig. 1*a*), caused mainly by scattering of O-star light off the free electrons in the W-R wind.

The different groups of polarimetric data spread over a 20 yr period are not sufficiently precise to allow verification of the suggested rate of increase of the orbital period (0.222 ± 0.018 s yr^{-1}) by Kornilov and Cherepashchuk (1979).

III. DETAILED ANALYSIS OF THE BINARY MODULATION

The determination of i and Ω from polarization data in the case of V444 Cyg is affected by two factors not included in the model of BME: (*a*) the eclipse of the W-R wind scatterers and (*b*) the eclipses of the light sources, after allowing for a component of interstellar polarization. Accurate values of i and Ω can be obtained from the new observations only if the eclipses and the interstellar polarization are properly taken into account. Only then can the eclipse of the scatterers around phase 0.5 be analyzed properly as well.

First, in order to tie down the double-wave orbital variations in polarization, we start by omitting the six eclipse-affected polarization observations between phases 0.4 and 0.6. Because of the gap so created, we limit the Fourier fit of equation (1) to the second harmonic terms only. First harmonic terms are found to be very small in all well-behaved W-R binaries with circular orbits observed so far (see especially the two WC7 + O binaries HD 97152 and HD 152270 in St.-Louis *et al.* 1987, hereafter Paper I). Figure 1*a* shows that this is also the case in V444 Cyg.

Second, we correct for the light curve eclipses. We adopt the approximation of Drissen *et al.* (1986*b*) which supposes that, coming from a much more extended area, the polarized light flux is negligibly affected by the light eclipses compared to the unpolarized light from the stars. The interstellar component of polarization (Q_{IS} and U_{IS}) does not depend on orbital phase. The corrected values to be used in equation (1) are then

$$Q_c = (Q - Q_{IS}) \frac{I_\varphi}{I_m} ,\quad U_c = (U - U_{IS}) \frac{I_\varphi}{I_m} , \tag{2}$$

where Q and U are the observed values, and I_φ/I_m is the ratio of the intensity at any phase φ to the maximum intensity seen between eclipses. This ratio is extracted from the light curve at 4789 Å given by Cherepashchuk and Khaliullin (1973).

The estimated interstellar position angle based on the stars surrounding V444 Cyg is $\theta_{IS} = 50\overset{\circ}{.}0 \pm 4\overset{\circ}{.}5$ (see Table 1 of Paper V). This result is not compatible with the value of U_{IS} that is obtained by forcing a fit to the model of BME (which we will not demonstrate here). Probably the most reliable method to estimate the interstellar component consists of calculating Q_0' and U_0', the center of the ellipse in the $Q'-U'$ plane when $\Omega = 0°$ and when there is no component of polarization from the interstellar medium (Q_0' and U_0' correspond to Q_0 and U_0 of the BME model for a symmetrical envelope about the orbital plane). In this case, we must have

$$U_0' = 0 ,\quad Q_0' = \tau_0(1 - 3\gamma_0) \sin^2 i . \tag{3}$$

For any angle Ω,

$$Q_c = Q' \cos \Omega - U' \sin \Omega ,\quad U_c = Q' \sin \Omega + U' \cos \Omega . \tag{4}$$

From an iterative calculation, it is easy to estimate simultaneously i, Ω, Q_{IS}, and U_{IS}. (Starting with the approximate value of $\Omega = 312°$ obtained by assuming $Q_{IS} = U_{IS} = 0$ in eqs. [2] and [3], one can calculate to a first approximation Q_{IS} and U_{IS}; then these values can be used to estimate a better value for Ω and again for Q_{IS} and U_{IS}, and so on.) Normally, it is not possible to apply this method since the term $\tau_0(1 - 3\gamma_0)$ requires *a priori* knowledge of the physical characteristics of the binary. However, in the case or V444 Cyg, these characteristics are better known than for other binaries; therefore, we will attempt to derive $\tau_0(1 - \gamma_0)$ first and then we will calculate i, Ω, Q_{IS}, and U_{IS}.

The parameter τ_0 is the effective Thomson-scattering optical depth integrated over all directions, while γ_0 is the inverse measure of the effective degree of flattening of the electron envelope toward the orbital plane. The expressions for τ_0 and $\tau_0\gamma_0$ are given by equation (7) of BME for an optically thin electron distribution:

$$\begin{aligned} \tau_0 &= \frac{3\sigma_t}{32\pi} \sum_{j=*W}^{*O} f_j \int_0^\infty \int_0^\pi \int_0^{2\pi} n_e(R_{*W}) \sin\theta_j \, dR_j \, d\theta_j \, d\phi_j \\ &= \tau_{*W} + \tau_{*O} , \\ \tau_0\gamma_0 &= \frac{3\sigma_t}{32\pi} \sum_{j=*W}^{*O} f_j \int_0^\infty \int_0^\pi \int_0^{2\pi} n_e(R_{*W}) \cos^2\theta_j \sin\theta_j \, dR_j \, d\theta_j \, d\phi_j \\ &= \tau_{*W}\gamma_{*W} + \tau_{*O}\gamma_{*O} . \end{aligned} \tag{5}$$

The index $j = *W$ and $*O$ indicates the contribution from the W-R star and its *O*-type companion, respectively. The quantity σ_t is the Thomson cross section for a single electron, while f_j is the ratio of the intensity of star j to the total intensity. As an example, for the O star:

$$\begin{aligned} f_{*O} &= \frac{I_{*O}}{I_{*O} + I_{*W}} = \left(1 + \frac{I_{*W}}{I_{*O}}\right)^{-1} \\ &= (1 + 10^{(M_{V*O} - M_{V*W})/2.5})^{-1} , \end{aligned} \tag{6}$$

in which M_V refers to the absolute visual magnitude (we assume that the observed blue light ratio of the two stars is the same as the visual light ratio). Furthermore, $n_e(R_{*W})$ is the electron density at a distance R_{*W} from the W-R star. Assuming (*a*) mass conservation: $\dot{M} = 4\pi R_{*W}^2 v\rho =$ constant, (*b*) the commonly used wind-velocity law of Castor and Lamers (1979): $v = v_\infty(1 - R_{\text{W-R core}}/R_{*W})^\beta$, with $\beta = \frac{1}{2}$, and (*c*) the W-R wind composed of totally ionized helium (see CEK): $n_e = 2\rho/m_{He}$, one finds:

$$n_e(R_{*W}) = \frac{\dot{M}}{2\pi m_{He} v_\infty} \frac{1}{R_{*W}^2(1 - R_{\text{W-R core}}/R_{*W})^{1/2}} , \tag{7}$$

where m_{He} is the mass of the helium nucleus and v_∞ is the terminal velocity of the wind. The increased electron opacity of the inner wind to optically thick values is allowed for in a crude way by forcing n_e to be equal to zero when $R_{*W} \leq 7\,R_\odot$. This is based on (*a*) the result of CEK: the radial opacity of the wind of V444 Cyg is significant ($\tau \geq 0.2$) out to two or three stellar radii and (*b*) the analysis given below of the Chandrasekhar-type polarization eclipses.

TABLE 2

PHYSICAL CHARACTERISTICS ADOPTED FOR V444 CYGNI

Parameter	Value	Reference
a	40 $R_\odot$	1
R_O	10 $R_\odot$	2, 3
$R_{\text{W-R core}}$	2.9 $R_\odot$	4
$\dot{M}$	$(1.0 \pm 0.2) \times 10^{-5}\ M_\odot\ \text{yr}^{-1}$	5, 6, 7, 8, 9
v_∞	(2500 ± 200) km s^{-1}	10, 4
M_{V*W}	$-4^{\text{m}}.2$	4
M_{V*O}	$-5^{\text{m}}.5$	11

REFERENCES.—(1) Münch 1950; (2) Kron and Gordon 1950; (3) Cherepashchuk 1975; (4) CEK; (5) Khaliullin, Khaliullin, and Cherepashchuk 1984; (6) Bieging, Abbott, and Churchwell 1982; (7) Barlow, Smith, and Willis 1981; (8) Khaliullin 1974; (9) Kornilov and Cherepashchuk 1979; (10) Eaton, Cherepashchuk, and Khaliullin 1985; and (11) Schmidt-Kaler 1982.

Due to the assumed spherical symmetry of the W-R wind about the W-R core,[2] the first terms in equation (5) yield:

$$\tau_{*W} = 3\tau_{*W}\gamma_{*W} . \quad (8)$$

Then the value of $\tau_0(1 - 3\gamma_0)$ depends only on τ_{*O} and $\tau_{*O}\gamma_{*O}$. These two terms are evaluated numerically from equation (5) using the geometrical relation:

$$R_{*W}^2 = R_{*O}^2 + a^2 - 2aR_{*O} \sin\theta_{*O} \cos\phi_{*O} , \quad (9)$$

where a is the orbital separation. The infinite limit of the integrals in equation (5) is replaced by $5a$; beyond this, it is easily shown that the contribution to the integrals is negligible.

With the physical characteristics of V444 Cyg (see Table 2) obtained from the photometric and spectroscopic analysis, one then finds:

$$\tau_0(1 - 3\gamma_0) = 0.205\% \pm 0.058\% .$$

The error estimated for $\tau_0(1 - 3\gamma_0)$ is dominated by the errors in $\dot{M}$ and v_∞.

Finally, Table 3 contains the coefficients of the Fourier fit for which the free parameters Q_{IS}, U_{IS}, i, and Ω satisfy equation (3). These parameters are given in Table 4: the resulting interstellar polarization is $Q_{\text{IS}} = 0.036\% \pm 0.035\%$ and $U_{\text{IS}} = -0.240\% \pm 0.039\%$ (or $P_{\text{IS}} = 0.243\% \pm 0.043\%$ and $\theta_{\text{IS}} = 139.^\circ3 \pm 3.^\circ6$, which is quite different from the estimate of Paper V obtained from the average polarization of the surrounding stars). The orbital inclination is now $78.^\circ7 \pm 0.^\circ5$ and $\Omega = 316.^\circ4 \pm 0.^\circ9$. Figure 2 shows, as a function of the orbital phase, Q' and U', which are the observed values simultaneously corrected for interstellar polarization and light curve effects. They are presented in the natural reference frame of the binary (after a rotation by $-\Omega$). The solid curves of Figure 2 represent the final Fourier fit calculated omitting the data between phase 0.4 and 0.6. As required by equation (3), U'_0 is almost equal to zero, and Q'_0 is very close to $0.205 \sin^2 i$.

The value of i obtained is very similar to the value given by Cherepashchuk (1975), $i = 78° \pm 1°$, from the analysis of the light curves with a new method more appropriate to the extended envelope of the W-R star. It is also compatible with the previous estimate from the light curve of Kron and Gordon (1950), $i = 78.^\circ4$.

[2] Note that Underhill and Fahey (1987) propose a disk-shaped wind extending in the orbital plane well beyond the two stars in V444 Cyg. We consider this to be unlikely in view of the high wind speeds in W-R stars and the fact that some well observed W-R stars do show polarimetric evidence for spherical winds (Paper I and Moffat 1988).

TABLE 3

HARMONIC COEFFICIENTS OF V444 CYGNI (DETAILED ANALYSIS)[a]

q_0	u_0	q_3	u_3	q_4	u_4
+0.1874	−0.0003	−0.1869	+0.0082	−0.0222	−0.0703
±0.0018	±0.0018	±0.0024	±0.0024	±0.0026	±0.0026

[a] In %.

The parameters Q_{IS} and U_{IS} are strongly dependent on the model used to describe Q'_0, τ_0, and $\tau_0\gamma_0$. The principal assumptions are: a scattering envelope symmetric about the orbital plane, single scattering only, and a radiating point source. The numerical value of $\tau_0(1 - 3\gamma_0)$ depends strongly on the stellar parameters adopted (Underhill and Fahey 1987 obtained $R_{\text{W-R core}} = 9\ R_\odot$ compared to 2.9 $R_\odot$ as used here; they also used $v_\infty = 1500$ km s^{-1}, compared to 2500 km s^{-1} from resonant UV lines; the best value may turn out to be between these two: see Williams and Eenens 1989). On the other hand, we find that the uncertainty in the interstellar component does not drastically affect the values obtained for i and Ω. We have also used a simplified method to represent the electron opacity in the W-R wind. In another model, where we neglect the electron opacity, i.e., we integrate close to the W-R star surface [for $R_{*W} \geq (2.9 + \epsilon)R_\odot$, with $\epsilon = 10^{-5}$ to avoid problems in evaluating the integrals at $R_{*W} = R_{\text{W-R core}}$, the value of $\tau_0(1 - 3\gamma_0)$ increases to 0.29%. For a larger cutoff radius of 10 $R_\odot$ instead of 7 $R_\odot$ as in the first calculation, we find $\tau_0(1 - 3\gamma_0) = 0.17\%$. However, in these two models the values of i and Ω are the same, within their error limits, as i and Ω from the first model with a cutoff radius of 7 $R_\odot$.

Table 4 also contains the moments of the electron distribution $\tau_0\gamma_3$ and $\tau_0\gamma_4$. These parameters describe the concentration of electrons (and of ions associated with them) within the orbital plane. The quantity $\lambda_2[= \frac{1}{2}\arctan(\gamma_4/\gamma_3)]$ is the angle between the bulk of the scattering material and the line joining the stars. With $\tau_0\gamma_4$ much larger than $\tau_0\gamma_3$, λ_2 is close to 0° or 90° ($\lambda_2 = -3.^\circ4$ or $86.^\circ6 \pm 0.^\circ5$). The small but significant deviation from 0° or 90° is, assuming the estimated error to be realistic, possibly due to the distortion of the electron envelope around the W-R star by its companion. On the other hand it may not be real, being the result of mathematical coupling, especially between Ω and λ_2.

TABLE 4

POLARIMETRIC PARAMETERS FOR V444 CYGNI (DETAILED ANALYSIS)

Parameter	Value
Q_{IS}	$0.036\% \pm 0.035\%$
U_{IS}	$-0.240\% \pm 0.039\%$
i	$78.^\circ7 \pm 0.^\circ5$[a]
Ω	$316.^\circ4 \pm 0.^\circ9$[a]
$\tau_0\gamma_3$	$(1.80 \pm 0.03) \times 10^{-3}$[a]
$\tau_0\gamma_4$	$(-0.21 \pm 0.03) \times 10^{-3}$[a]
λ_2	$-3.^\circ4 \pm 0.^\circ5$[a]

[a] The uncertainty is calculated according to the method of propagating errors.

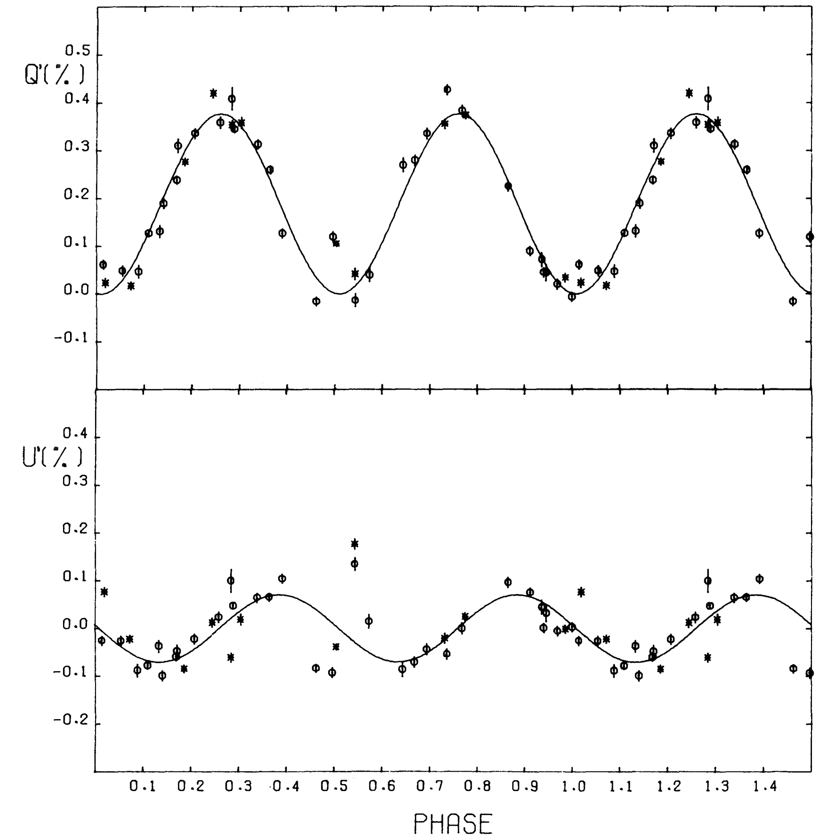

FIG. 2.—Stokes parameters Q' and U' for V444 Cyg plotted against orbital phase (ephemeris as in Fig. 1). Q' and U' refer to the observed parameters corrected for light eclipses, after subtracting off the interstellar component. They are presented in the natural reference frame of the binary (major axis of the $Q'-U'$ ellipse pointing in the Q' direction). Solid curves represent the best fit of a Fourier series of second-harmonic terms only, omitting the data at phases 0.5 ± 0.1, the main interval of the scatterers eclipse.

IV. WIND ECLIPSE

The presence of the wind eclipse, by analogy with the effect predicted by Chandrasekhar for early-type stars, allows one to explore another polarimetric method for studying the geometry of the binary and the electron density around the W-R star. Polarimetric models of the scattering eclipses have been presented by Piirola (1980) for the early-type spectroscopic binary U Cep, by Kemp *et al.* (1983) for Algol, and by Brown and Fox (1989) for Be stars. We propose here a simple model for V444 Cyg that reproduces the observed variation due to the eclipse of the scatterers using the known characteristics of the binary. In this model, the electron envelope of the W-R star is assumed to be spherically symmetric about the W-R star.

The model should normally calculate the resulting polarization Q_e and U_e created by the W-R star light on its noneclipsed electrons. The resulting polarization would be equal to zero if there were no occulting body. Under these circumstances, Q_e and U_e are equal, but with opposite sign, to the polarization created by the *eclipsed* electrons, whose domain is easier to define. We adopt this approach here. These eclipsed electrons are contained in a cylinder of radius R_0 (the radius of the O star) and extending parallel to the line of sight (refer to Fig. 3). The cylinder is projected toward the observer to include the electrons on the near side of the O star that cannot "see" the W-R star light. In reality, these electrons are contained in a conical volume with apex centered on the W-R star. However, the density is smaller at this larger distance from the W-R star, and in any case, the contribution to the net polarization from these electrons is also relatively small (nearly forward scattering), making the approximation quite acceptable. Close to orbital phase 0.5, when the cylinder intersects the permanent shadow behind the W-R star, the electrons in common to the two shadows behind the W-R star are omitted from the calculation, in correspondence with reality.

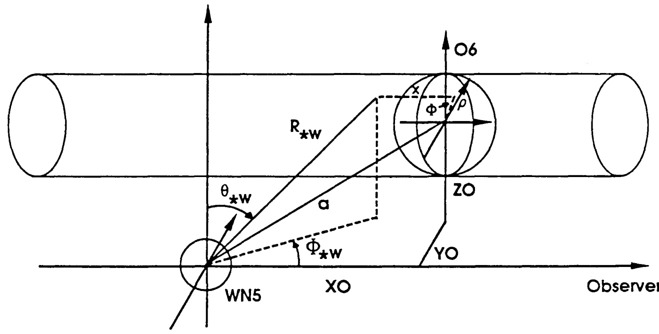

FIG. 3.—Schematic diagram of the binary V444 Cyg showing the geometry of the scatterers eclipse. Symbols are described in the text.

Q_e and U_e are deduced from equation (3) of BME for an optically thin configuration. Their transformation to a cylindrical coordinate system centered on the O star (see Fig. 3) gives:

$$Q_e = -\frac{3\sigma_t}{16\pi} f_{*W} \int_{-\infty}^{+\infty} \int_0^{R_O} \int_0^{2\pi} \frac{n_e(R_{*W})}{R_{*W}^4} \times [(\rho \sin \phi + YO)^2 - (\rho \cos \phi + ZO)^2] \rho \, dx \, d\rho \, d\phi \,,$$

$$U_e = -\frac{3\sigma_t}{16\pi} f_{*W} \int_{-\infty}^{+\infty} \int_0^{R_O} \int_0^{2\pi} \frac{2n_e(R_{*W})}{R_{*W}^4} \times (\rho \sin \phi + YO)(\rho \cos \phi + ZO) \rho \, dx \, d\rho \, d\phi \,, \quad (10)$$

where $n_e(R_{*W})$ is the same electron density variable as in equation (7), which directly relates Q_e and U_e to the ratio $\dot{M}/v_\infty$. The phase variation of f_{*W} is taken to be:

$$f_{*W} = \frac{I_{*W}}{I_\varphi} = \frac{(I_{*O}/I_{*W} + 1)^{-1}}{I_\varphi/I_m} = \frac{(1 + 10^{(M_{V*W} - M_{V*O})/2.5})^{-1}}{I_\varphi/I_m} \,, \quad (11)$$

where I_φ is the light intensity at phase φ, i.e., $(I_{*O} + I_{*W})_\varphi$, and I_m is the maximum light between eclipses. From Figure 3:

$$R_{*W}^2 = (x + XO)^2 + (\rho \sin \phi + YO)^2 + (\rho \cos \phi + ZO)^2 \,, \quad (12)$$

where (XO, YO, ZO) is the position of the O star relative to the W-R star:

$$XO = a \sin i \cos \zeta \,, \quad YO = a \sin \zeta \,, \quad ZO = a \cos i \cos \zeta \,, \quad (13)$$

in which $\zeta = 360°(0.5 - \varphi)$.

Q_e and U_e in equation (10) are numerically integrated for different values of the phase, using $i = 78°.7$ and the physical characteristics of Table 2. Similarly as in equation (5), the infinite limits of the integrals in equation (10) are replaced by $\pm 5a$. The calculations are also repeated with three different cutoff radii around the W-R star: $R_c = 10$, 4, and $(2.9 + \epsilon)\, R_\odot$ (with $\epsilon = 10^{-5}$, as explained in the previous section). The electrons contained in and behind a sphere of radius R_c, centered on the W-R star, are not considered in the integrals.

Figure 4 shows, plotted against phase, the three different polarization eclipse curves calculated for Q_e and U_e. Note that our results are very similar to those obtained for the *spherical component* of the hot star in the symbiotic binary U Cep (see Figs. 4*a*, 4*b* of Piirola 1980). The filled circles in Figure 4 (values are given in Table 5) represent the corrected observed data Q' and U' between phases 0.4 and 0.6, after subtracting off the smooth double-wave polarimetric modulation of the light from the O star, as shown in Figure 2.

A model with $R_c \simeq 7\, R_\odot$ ($\simeq 2$–$3R_{\text{W-R core}}$) would lead to an acceptable fit (considering the small number of data points collected and the small number of free parameters). There are two main factors in support of the above model calculation, which neglects the electrons within and behind a sphere centered on the W-R star with radius $R_c \simeq 7\, R_\odot$. First, there is the increased opacity of the inner wind (which is dramatic within two or three stellar radii, according to the empirical data of CEK). This enhances multiple scattering, which tends to cancel out any systematic polarization. Second, there is the fact that our point source model neglects the real, finite surface of the radiating source. As demonstrated analytically first by Rudy (1978) and then more precisely by Cassinelli, Nordsieck, and Murison (1987) and Brown, Carlaw, and Cassinelli (1989), the polarization based on a point source model is significantly overestimated for those scatterers that are located within

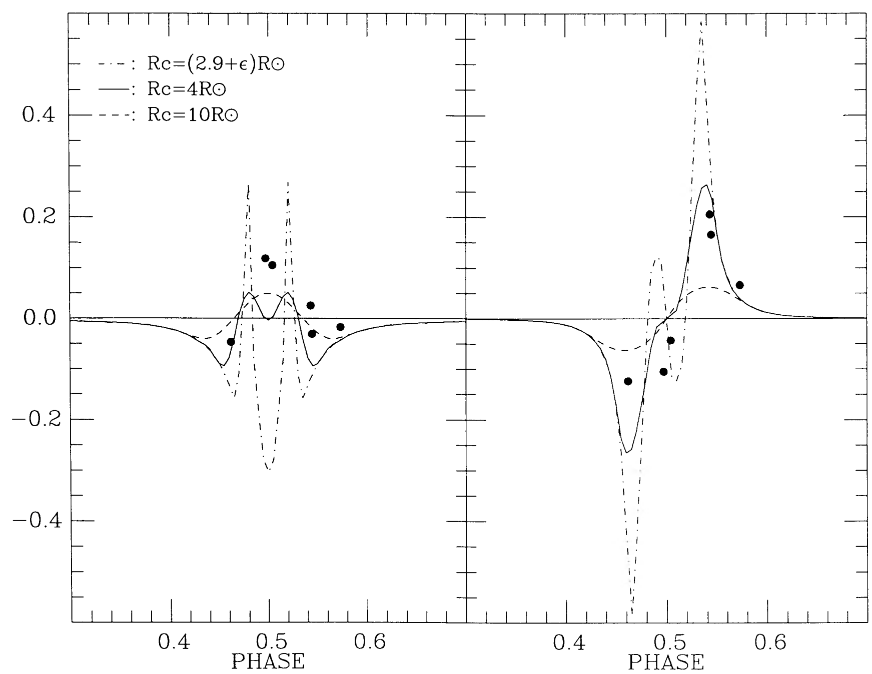

FIG. 4.—Stokes parameters Q_e (*left*) and U_e (*right*) for V444 Cyg due to the W-R wind eclipse only. The filled circles are the observed values at phase 0.5 ± 0.1 obtained after subtracting off the orbital fit to Q' and U' indicated in Fig. 2. The three solid curves are from a model (eq. [10]) using three different values of R_c as indicated.

TABLE 5

Q_e AND U_e OBSERVED FOR V444 CYGNI

φ	$Q_e(\%)$	$U_e(\%)$
0.462....................	−0.047	−0.123
0.497....................	0.118	−0.104
0.504....................	0.105	−0.043
0.543....................	0.025	0.206
0.544....................	−0.031	0.166
0.573....................	−0.017	0.066

about a stellar radius from the surface of the radiating source. Using the very small cutoff radius of $(2.9 + \epsilon) R_\odot$ clearly leads to an overestimate of the observed polarization due to the eclipse of scatterers, particularly at phase 0.5.

An electron distribution in an equatorial disk around the W-R star would not, based on the calculation of Piirola (1980; his Fig. 4*c*) for U Cep, reproduce our observations.

V. SUMMARY

A simplified analysis of the present polarimetric data for V444 Cyg compared with the previous results of HM, RK, and PL reveals similar values of i and Ω and a constant mass-loss rate over the last 20 yr. Using the BME model of polarimetric modulation in a binary system, after allowing for an interstellar component and for eclipses of the stars and of the scatterers, we obtain $i = 78.^\circ7 \pm 0.^\circ5$, which agrees well with the photometric value of Cherepashchuk (1975), $i = 78^\circ \pm 1^\circ$, and of Kron and Gordon (1950), $i = 78.^\circ4$. The value of Ω deduced here is $316.^\circ4 \pm 0.^\circ9$. The interstellar contribution, $Q_{\rm IS} = 0.036\% \pm 0.035\%$ and $U_{\rm IS} = -0.240\% \pm 0.039\%$, is calculated simultaneously with i and Ω, assuming an electron envelope symmetric around the W-R star, the wind-velocity law of Castor and Lamers (1979), single scattering, and an optically thick wind inside $2\text{–}3R_{\rm W\text{-}R\ core}$.

The present observations are of sufficiently high precision to show for the first time in a W-R binary the polarization eclipse effect of scatterers predicted over 40 yr ago for early-type stars in general by Chandrasekhar (1946). Although small in number, the polarization data at phases 0.5 ± 0.1, where the O companion blocks the brightest part of the W-R wind, are fitted reasonably well by a simple, spherically symmetric model for the W-R wind scatters. Our model calculations give a cutoff radius of 7 $R_\odot$ (to simulate the finite size of the radiating source and the possibility of multiple scattering in the inner wind). This result (which is compatible with the value of $2\text{–}3R_{\rm W\text{-}R\ core}$ required by Rudy 1978) supports the possibility of a small core radius of 2.9 $R_\odot$ for the W-R star. With the accumulation of more high-quality data points around phase 0.5, we expect that modeling of the polarization eclipse will provide a reliable estimate of the ratio of $\dot{M}/v_\infty$ for V444 Cyg.

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