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POLARIZATION VARIABILITY AMONG WOLF-RAYET STARS. VIII. EMISSION LINES VERSUS CONTINUUM IN WR + O BINARIES[1]

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ABSTRACT

Phase-dependent, linear polarization observations of two noneclipsing WC7 + O binaries (HD 97152 and HD 152270) with periods of ~8 days show that the strongest emission-line complex (C III/IV 465.0 nm + He II 468.6 nm) does not vary significantly in polarization (peak-to-peak amplitude <0.05%), in contrast to the continuum (~0.7%). In fact, we deduce that there is no phase-dependent intrinsic polarization in the lines, and that for HD 152270 the remaining static polarization shows no evidence for intrinsic polarization beyond that obtained from a simple binary model. (For HD 97152, this is less clear, due probably to some instrumental anomaly.) This is as expected in WR + O binaries, if the orbital polarization modulation is due mainly to scattering of O-companion light off free electrons in a hot, dense, spherically symmetric WR wind. In such systems, there is little or no asymmetric distribution of free electrons off which WR emission-line and continuum photons can scatter and produce detectable polarization.

Similarly but not identically during our 1991 June observations, the peculiar 3.77 day variable WN5 star EZ CMa (HD 50896) shows a small but significant variation in emission-line polarization (~0.3%) compared to its large continuum modulation amplitude (~1.6%). However, unlike WR + O binaries, the strong He II 468.6 nm line in EZ CMa does have a small, constant but nonzero intrinsic component of polarization.

Subject headings: binaries: close — polarization — stars: individual (HD 50896, HD 97152, HD 152270) — stars: Wolf-Rayet

1. INTRODUCTION

Wolf-Rayet (WR) stars are among the few types of stars with sufficiently hot, dense, and rapidly expanding envelopes in the form of winds, that produce enough free electrons to scatter and polarize a detectable quantity of light from a bright companion star. The typical phase-dependent, double-wave modulation in the Stokes linear polarization parameters Q and U that results, provides valuable information on the WR mass-loss rates and orbital inclinations (hence the stellar masses, once the radial velocity orbits are known) for WR stars with close O-type companions (e.g., St-Louis et al. 1988).

Several basic assumptions are involved in the model conversion of phase-dependent polarization variability of WR + O systems into $\dot{M}_{WR}$ and i: (1) since we are dealing with electron scattering at optical wavelengths, the degree of polarization, as measured by the amplitude of modulation, is assumed to be wavelength independent; (2) the WR wind is assumed to be spherically symmetric; (3) the O-companion wind is assumed to be negligible; and (4) wind interaction and eclipse effects are ignored. These being the case, it is expected that only the (continuum) radiation from the O star will be partially polarized by scattering off free electrons in the asymmetrically placed WR wind, while the continuum + emission-line photons from the WR star will be unpolarized, as they scatter off the spherically symmetric WR wind itself. Because it is normally only the WR star which reveals emission lines (in the visible), this in turn means that the observed emission lines in the visible (or elsewhere) of WR + O systems are expected to be intrinsically unpolarized and nonvariable. If in fact one finds the emission lines to be intrinsically polarized, one would conclude that one or more of the above assumptions may not be valid. The purpose of this paper is to check these assumptions by examining the polarization from strong emission lines compared to the continuum at different wavelengths in WR + O binaries.

2. OBSERVATIONS

It was not our goal to observe all known WR + O binaries, nor to carry out line-resolved spectropolarimetry. Our present aim is to examine, using high-precision, time-dependent, narrow-band on-line and broad-band polarimetry, at least one (we take two to be safe) well-known WR + O binary, with (*a*) moderately short period, so that the amplitude of polarization variability is not too small, but (*b*) not so short a period that wind interaction effects become important, and (*c*) of relatively low orbital inclination, so that wind eclipse effects will be minimized. Two such stars (see St-Louis et al. 1988) are HD 97152 = WR 42 (WC7 + O7 V, $P = 7\overset{d}{.}886$, $i = 44° \pm 3°$) and HD 152270 = WR 79 (WC7 + O 5–8, $P = 8\overset{d}{.}8908$, $i = 45° \pm 3°$). Note that both systems have circular orbits and are very similar both in stellar content and orbital parameters; this has the advantage that we will be less sensitive to anomalies peculiar to any particular star. We also observed a third star, HD 50896 = WR 6 (WN5, $P = 3\overset{d}{.}766$, $i \approx 65°$); it does not appear to have a massive companion but is known to show

[1] Based on observations collected at the European Southern Observatory.

strong depolarization in the observed emission lines (McLean et al. 1979; Schulte-Ladbeck et al. 1990, 1991).

In order to separate intrinsic from interstellar (IS) polarization, we obtained simultaneous four-color (*UBVR*) broad-band polarimetry at different orbital phases for all three stars. In order to separate line from continuum polarization, we added another filter: as it turns out, a Strömgren *b* filter (in particular ours at 467.0 nm, FWHM = 17.0 nm) nicely isolates the very strong C III/IV emission feature centered at 465.0 nm with FWHM typically about 5 nm in WC stars, together with He II 468.6 nm. The latter is also the strongest line seen in WN stars such as WR 6. This filter by itself does not completely isolate the emission-line flux; to do this properly, we compare the intermediate-band *b* data with broad-band *B* data, which are much less affected by emission lines.

The data (Table 1) were obtained during 8 nights in 1991 June at the Danish 1.5 m telescope at the European Southern Observatory (ESO) with the simultaneous five-channel polarimeter, built at the Turku University Observatory (Piirola 1973, 1988; Korhonen, Piirola, & Reiz 1984). The *I*-band data were not used for the present observations, due to technical problems with the *I*-photometer. Calibration of polarization angles in each filter was carried out using standard polarized stars in the usual way. The efficiency was close to 100% at all wavelengths. Nonpolarized standards were also observed in order to eliminate the small level of instrumental polarization, to within an uncertainty less than ±0.01% in each waveband.

TABLE 1A

POLARIMETRIC OBSERVATIONS OF WR 42

Filter[a]	J.D. (2,440,000+)	Phase[b]	Q	U	σ
U	8411.6120	0.278	−0.683%	−0.264%	0.034%
	8413.6824	0.540	−0.450	−0.411	0.049
	8414.6235	0.660	−0.455	−0.141	0.023
	8415.6614	0.791	−0.658	−0.540	0.034
	8416.5957	0.910	−0.482	−0.675	0.017
	8417.5239	0.027	−0.195	−0.455	0.021
B	8411.6120	0.278	−0.688	−0.440	0.032
	8413.6824	0.540	−0.331	−0.569	0.026
	8414.6235	0.660	−0.455	−0.332	0.021
	8415.6614	0.791	−0.576	−0.630	0.028
	8416.5957	0.910	−0.461	−0.749	0.013
	8417.5239	0.027	−0.306	−0.573	0.019
V	8411.6120	0.278	−0.691	−0.473	0.026
	8413.6824	0.540	−0.542	−0.532	0.047
	8414.6235	0.660	−0.621	−0.347	0.023
	8415.6614	0.791	−0.791	−0.615	0.073
	8416.5957	0.910	−0.508	−0.823	0.024
	8417.5239	0.027	−0.280	−0.652	0.052
R	8411.6120	0.278	−0.691	−0.514	0.024
	8413.6824	0.540	−0.297	−0.583	0.018
	8414.6235	0.660	−0.481	−0.396	0.023
	8415.6614	0.791	−0.594	−0.623	0.027
	8416.5957	0.910	−0.487	−0.795	0.016
	8417.5239	0.027	−0.281	−0.612	0.021
b	8411.6356	0.281	−0.596	−0.475	0.032
	8413.7068	0.543	−0.439	−0.606	0.029
	8414.6556	0.664	−0.505	−0.445	0.033
	8415.6341	0.788	−0.553	−0.538	0.022
	8416.5686	0.906	−0.407	−0.671	0.025
	8417.5454	0.030	−0.405	−0.578	0.032

[a] Central wavelengths and bandpasses (FWHM) here and in Tables 1*B*, and 1*C* are 358 (71), 439 (75), 535 (82), 680 (178), and 467 (17) nm.

[b] Based on time of passage of the WR component in front, $T(0)$ = JD 2,442, 463.34 + 7.886E

TABLE 1B

POLARIMETRIC OBSERVATIONS OF WR 79

Filter	J.D. (2,440,000+)	Phase[a]	Q	U	σ
U	8411.7173	0.804	−0.314%	0.124%	0.057%
	8413.8805	0.047	−0.015	−0.424	0.090
	8414.7990	0.151	−0.482	−0.408	0.058
	8415.8585	0.270	−0.368	−0.001	0.062
	8416.7591	0.371	0.004	0.061	0.013
	8417.6842	0.475	0.144	−0.294	0.024
B	8410.8729	0.709	−0.614	−0.127	0.040
	8411.7173	0.804	−0.337	0.041	0.029
	8413.8737	0.047	−0.242	−0.466	0.035
	8414.7990	0.151	−0.433	−0.376	0.021
	8415.8585	0.270	−0.405	0.000	0.024
	8416.7591	0.371	−0.097	−0.018	0.012
	8417.6842	0.475	0.006	−0.323	0.022
V	8410.8729	0.709	−0.574	−0.202	0.056
	8411.7173	0.804	−0.328	0.126	0.036
	8413.8737	0.047	−0.254	−0.485	0.035
	8414.7990	0.151	−0.507	−0.398	0.035
	8415.8585	0.270	−0.536	−0.042	0.036
	8416.7591	0.371	−0.117	−0.038	0.033
	8417.6842	0.475	−0.015	−0.352	0.027
R	8410.8695	0.709	−0.535	−0.138	0.040
	8411.7173	0.804	−0.402	0.078	0.021
	8413.8737	0.047	−0.267	−0.426	0.019
	8414.7990	0.151	−0.511	−0.367	0.023
	8415.8585	0.270	−0.479	0.052	0.020
	8416.7530	0.371	−0.167	0.025	0.023
	8417.6842	0.475	−0.075	−0.276	0.023
b	8410.8893	0.711	−0.329	−0.200	0.029
	8411.7331	0.806	−0.333	−0.076	0.017
	8413.9201	0.052	−0.190	−0.438	0.050
	8414.7820	0.149	−0.390	−0.267	0.024
	8415.8375	0.268	−0.356	−0.125	0.015
	8416.7309	0.368	−0.224	−0.104	0.017
	8417.7120	0.478	−0.108	−0.280	0.052

[a] Based on time of passage of the WR component in front, $T(0)$ = JD 2,441, 158.60 + 8.8908E.

3. RESULTS AND DISCUSSION

The observed Stokes parameters $Q = P \cos 2\theta$ and $U = P \sin 2\theta$ are plotted versus phase for each star and each filter in Figure 1. Normally, one would, in the context of the theory of optically thin, corotating scattering envelopes (see Brown, McLean, & Emslie 1978, hereafter BME; Rudy & Kemp 1978), fit a weighted, simultaneous single and double wave as follows:

$$Q = q_0 + q_1 \cos 2\pi\phi + q_2 \sin 2\pi\phi + q_3 \cos 4\pi\phi + q_4 \sin 4\pi\phi , \quad (1)$$

$$U = u_0 + u_1 \cos 2\pi\phi + u_2 \sin 2\pi\phi + u_3 \cos 4\pi\phi + u_4 \sin 4\pi\phi , \quad (2)$$

where ϕ is the orbital phase. This proved indeed necessary for WR 6 (as previously: see Drissen et al. 1989). However, in view of the relatively small number of data points here and past experience (St-Louis et al. 1988), the well-behaved binaries WR 42 and WR 79 were fitted with only second harmonics, i.e., in $4\pi\phi$ (in addition to the zero point). From Figure 1 we also note the following:

1. Variations in each of Q and U are generally in phase in each filter.
2. The amplitudes and phases of Q and U in WR 79 are

TABLE 1C

POLARIMETRIC OBSERVATIONS OF WR 6

Filter	J.D. (2,440,000+)	Phase[a]	Q	U	σ
U	8412.4767	0.809	0.688%	−0.746%	0.019%
	8414.4685	0.338	0.036	−0.269	0.046
	8415.4767	0.606	0.265	−0.548	0.030
	8416.4737	0.870	0.737	−0.720	0.026
	8417.4749	0.136	−0.188	−0.986	0.014
B	8412.4767	0.809	0.595	−0.611	0.016
	8414.4685	0.338	0.188	−0.307	0.022
	8415.4767	0.606	0.384	−0.495	0.013
	8416.4737	0.870	0.735	−0.601	0.011
	8417.4749	0.136	0.105	−0.835	0.012
V	8412.4767	0.809	0.694	−0.705	0.032
	8414.4685	0.338	−0.050	−0.258	0.080
	8415.4767	0.606	0.443	−0.443	0.060
	8416.4737	0.870	0.759	−0.676	0.032
	8417.4749	0.136	0.163	−0.975	0.032
R	8412.4643	0.806	0.518	−0.550	0.035
	8414.4685	0.338	0.221	−0.243	0.024
	8415.4829	0.607	0.375	−0.446	0.030
	8416.4792	0.872	0.556	−0.466	0.036
	8417.4804	0.138	0.036	−0.647	0.052
b	8412.4753	0.809	0.466	−0.435	0.013
	8414.4846	0.342	0.371	−0.309	0.035
	8415.4597	0.601	0.354	−0.365	0.028
	8416.4572	0.866	0.526	−0.362	0.023
	8417.4614	0.133	0.266	−0.544	0.022

[a] Based on time of average maximum light between 1980 and 1985 (Lamontagne et al. 1986), $T(0)$ = JD 2,446,153.61 + 3.766E.

similar to those seen in previous data, while only the amplitudes agree for WR 42, for which the orbital ephemeris is not yet well enough established (St-Louis et al. 1987). However, in view of the small number of present data points, we do not attempt to extract an orbital inclination from them.

3. The amplitudes and phases of Q and U in WR 6 are, not surprisingly, similar in general, but different in detail, compared to previous polarization observations (cf. Drissen et al. 1989).

4. In each star, the amplitude of variation in the intermediate-band on-line b filter is significantly lower than the amplitude in the broad-band B filter (both filters have similar central wavelengths).

5. The zero-point of variations in the emission-sensitive b filter is similar to that in the B filter for the two WC7 + O binaries, but not for WR 6, where there is a significant shift (~0.2%) in the Stokes U parameter.

We now explore in more detail how the amplitudes and zero-points change with wavelength. Figure 2 shows the fitted trajectories of orbital (or other) motion in the Q-U plane for each star. Note how a first harmonic fit to the residuals after a second harmonic fit to WR 42 and WR 79 produces small, insignificant (in a quadratic sense) components. In Table 2 we give the coefficients of the unweighted $Q(\phi)$, $U(\phi)$ fits (all in percent), along with variability amplitudes. From these values, and from Figure 3, we see how the amplitudes vary with wavelength. We note that there is a slight trend in the WC7 + O binaries, and a clear trend in WR 6, for (*i*) an increase in amplitude for shorter wavelengths, and (*ii*) a sharp dip in amplitude in the b filter, as noted above. While the general trend in (*i*) may be at least partly due to differing contributions of depolarized line flux in each filter or simply different colors of the WR (cooler) and O stars (we do not have enough, e.g., spectropolarimetric information to sort this problem out in the case of WR 42 and WR 79) but is likely a real effect intrinsic to the WR star in WR 6 (cf. Schulte-Ladbeck et al. 1991), the strong trend in (*ii*) can be accounted for almost wholly by nonpolarized emission-line flux as follows.

Assuming all the lines in a given filter have the same (a priori unknown) polarization, and polarization degrees are small and thus vectorially additive, the polarized flux at any given time and in any given filter can be formally written as

$$Q(F_c + F_l) = (Q_c + Q_{\rm IS})F_c + (Q_l + Q_{\rm IS})F_l \, , \quad (3)$$

$$U(F_c + F_l) = (U_c + U_{\rm IS})F_c + (U_l + U_{\rm IS})F_l \, , \quad (4)$$

where Q, U are the observed degrees of polarization (Stokes parameters), F_c and F_l are the continuum and line fluxes observed in the filter of width W (taken to be the FWHM) and Q_c, Q_l, $Q_{\rm IS}$, U_c, U_l, $U_{\rm IS}$ are the degrees of polarization in the (pure) continuum, line emission, and interstellar medium. Taking W_e as the equivalent width of all the lines falling together in the filter, we define $\alpha = W_e/W = F_l/F_c$ and get

$$Q = Q_{\rm IS} + Q_c/(1 + \alpha) + Q_l/(1 + 1/\alpha) \, , \quad (5)$$

$$U = U_{\rm IS} + U_c/(1 + \alpha) + U_l/(1 + 1/\alpha) \, . \quad (6)$$

By considering first the amplitudes of variation ΔQ, ΔU we can eliminate the effect of constant IS polarization and write

$$\Delta Q = \Delta Q_c/(1 + \alpha) + \Delta Q_l/(1 + 1/\alpha) \, , \quad (7)$$

$$\Delta U = \Delta U_c/(1 + \alpha) + \Delta U_l/(1 + 1/\alpha) \, . \quad (8)$$

Now we compare the two filters B and b, assuming both have practically the same wavelength, so that ΔQ_c, ΔU_c, ΔQ_l, and ΔU_l (the four "unknowns") are also the same in both filters:

$$\Delta Q_b = \Delta Q_c/(1 + \alpha_b) + \Delta Q_l/(1 + 1/\alpha_b) \, , \quad (9)$$

$$\Delta U_b = \Delta U_c/(1 + \alpha_b) + \Delta U_l/(1 + 1/\alpha_b) \, ; \quad (10)$$

$$\Delta Q_B = \Delta Q_c/(1 + \alpha_B) + \Delta Q_l/(1 + 1/\alpha_B) \, , \quad (11)$$

$$\Delta U_B = \Delta U_c/(1 + \alpha_B) + \Delta U_l/(1 + 1/\alpha_B) \, . \quad (12)$$

Here we have four equations in four unknowns. Solving yields

$$\Delta Q_l = [\Delta Q_b(1 + \alpha_b) - \Delta Q_B(1 + \alpha_B)]/(\alpha_b - \alpha_B) \, , \quad (13)$$

$$\Delta U_l = [\Delta U_b(1 + \alpha_b) - \Delta U_B(1 + \alpha_B)]/(\alpha_b - \alpha_B) \, ; \quad (14)$$

$$\Delta Q_c = [\Delta Q_b(1 + 1/\alpha_b) - \Delta Q_B(1 + 1/\alpha_B)]/(1/\alpha_b - 1/\alpha_B) \, , \quad (15)$$

$$\Delta U_c = [\Delta U_b(1 + 1/\alpha_b) - \Delta U_B(1 + 1/\alpha_B)]/(1/\alpha_b - 1/\alpha_B) \, . \quad (16)$$

Taking W_b = 17 nm and W_B = 75 nm, we obtain values of α_b and α_B for each star, based on emission line W_e's of the dominating lines in b and B, assumed not to vary in time; C III/IV 465.0 + He II 468.6, of 37.2 nm in WR 42 and 31.6 nm in WR 79 (Smith, Shara, & Moffat, 1990); and 33.5 nm in b, 50.0 nm in B for WR 6 (Smith & Kuhi 1981). These lead to values of ΔQ and ΔU for the continuum and line emission as listed in Table 3. It is clear there that while the true continuum amplitudes near 460 nm are about 40% larger than in the B filter for WR 42 and WR 79, the pure line-emission amplitudes are compatible with zero at the 1 σ level on average. For WR 6 the

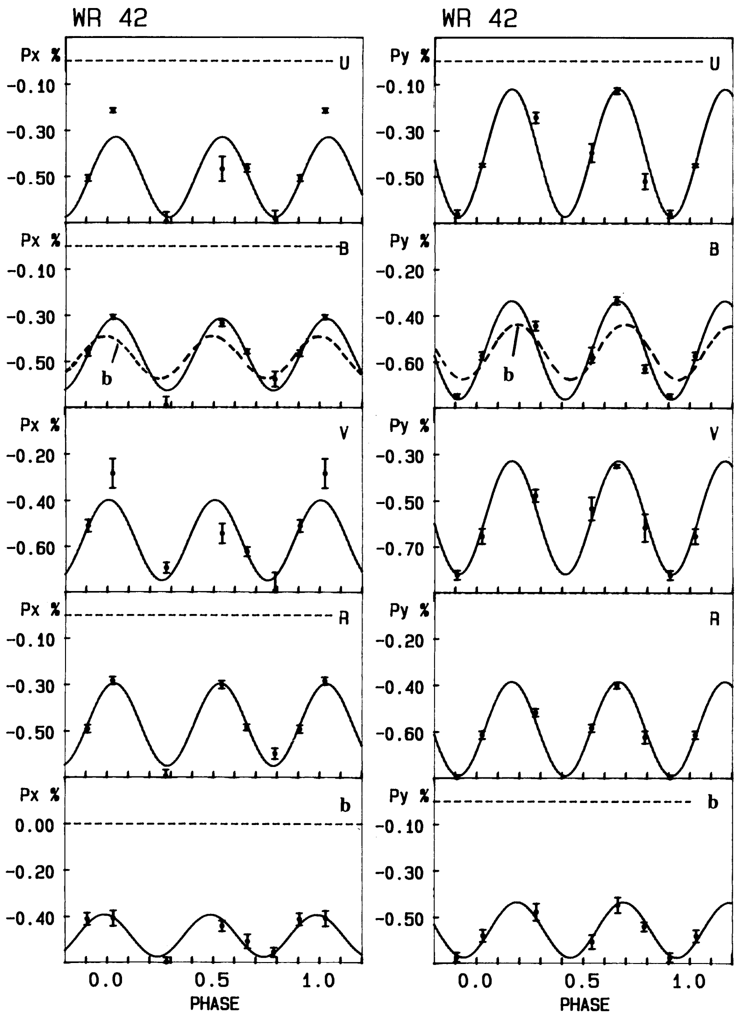

FIG. 1a

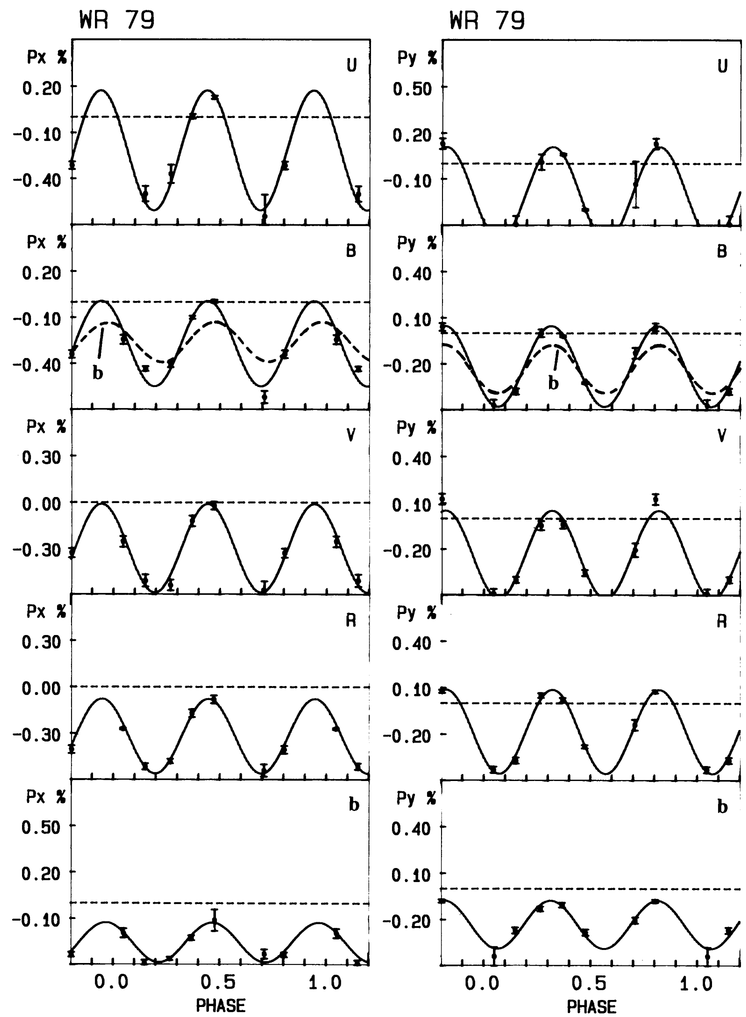

FIG. 1b

FIG. 1.—(*a*) Stokes linear polarization parameters, P_x (=Q) and P_y (=U) vs. orbital phase (cf. Table 1) for WR 42 in different filters. The curves are second harmonic fits to the data (cf. Table 2), shown with 2 σ error bars. The *b*-filter curves are also shown superposed on the *B* curve + data, for comparison. (*b*) As in (*a*), but for WR 79. (*c*) As in (*a*), but for WR 6 and for fits including first *and* second harmonics.

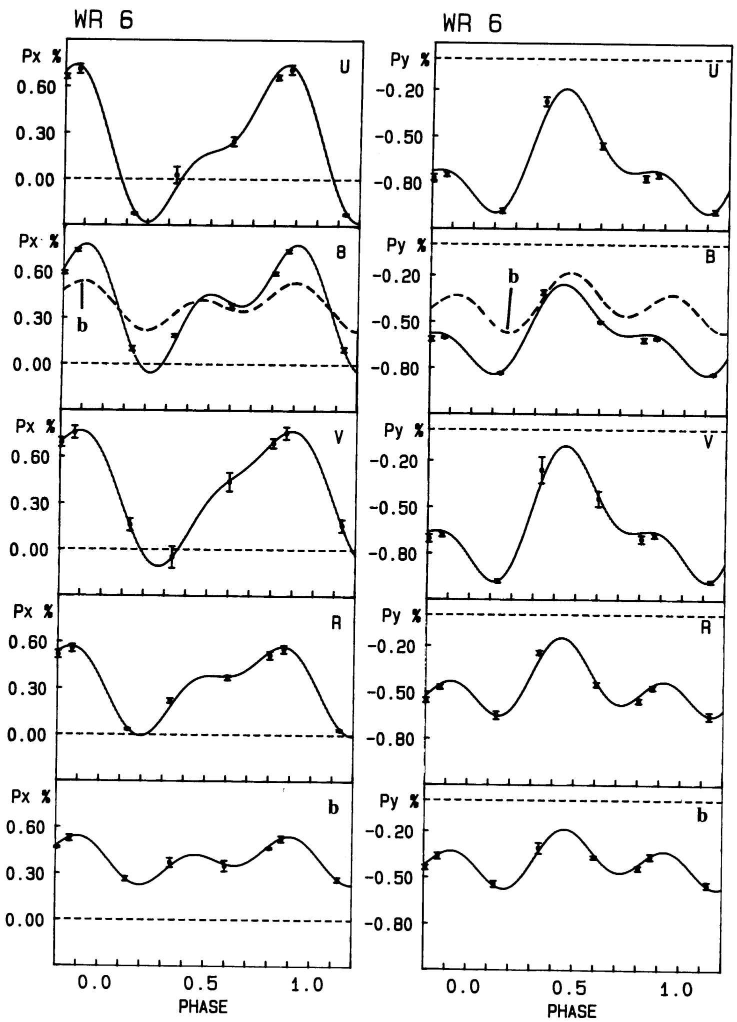

FIG. 1c

reduction in the B filter compared to the pure continuum amplitude is equally dramatic. However, a small component of variability in Q_l is seen in WR 6, although unknown variability of the line profiles in WR 6 (see, e.g., Firmani et al. 1980) may also account for the nonzero, *negative* value of ΔQ_l.

We now turn to the constant component of polarization given by q_0, u_0 for each filter and star in Table 2. In the case of the well-known binaries WR 42 and WR 79, q_0, u_0 still contain a small but predictable, fixed component of intrinsic polarization from the binary orbit, which was not allowed for explicitly in equations (1) and (2). According to BME for an optically thin electron cloud located symmetrically around one of the stars ($\gamma_4 = 0 = \gamma_1 = \gamma_2$), with the polarization axis of symmetry rotated by $\Omega°$ counterclockwise from the Q axis in the Q-U plane, one would have

$$Q = q_0' + \tau_0[\sin^2 i \cos \Omega - (1 + \cos^2 i) \cos \Omega \cos 4\pi\phi - 2 \cos i \sin \Omega \sin 4\pi\phi] , \quad (17)$$

$$U = u_0' + \tau_0[\sin^2 i \sin \Omega - (1 + \cos^2 i) \sin \Omega \cos 4\pi\phi - 2 \cos i \cos \Omega \sin 4\pi\phi] , \quad (18)$$

where q_0', u_0' are the true interstellar values (unless inflicted by intrinsic nonzero polarization if, e.g., the WR winds are flattened) and τ_0 is an optical depth parameter. Comparing with equations (1) and (2) with first harmonics set to zero, we deduce that

$$q_0' = q_0 + q_3 \sin^2 i/(1 + \cos^2 i) , \quad (19)$$

$$U_0' = u_0 + u_3 \sin^2 i/(1 + \cos^2 i) . \quad (20)$$

We apply equations (19) and (20) to WR 42 and WR 79 using the well-established values of i noted in § 2 and q_0, u_0, q_3, u_3 from Table 2A. Note that the absolute differences $|q_0' - q_0|$, $|u_0' - u_0|$ are small, $\leq 0.1\%$. For WR 6 we do not apply these corrections, since it is not clear for that star whether the BME binary model applies; we simply take q_0, u_0 directly after a dual harmonic fit.

We now attempt to search for a constant intrinsic component of polarization in q_0', u_0' for WR 42 and WR 79, or q_0, u_0 in WR 6 (*UVR* data only, where the influence of line polarization is relatively small). To do this we assume that these quantities can be expressed, in the simplest case, by the sum of an intrinsic, constant, wavelength-independent term

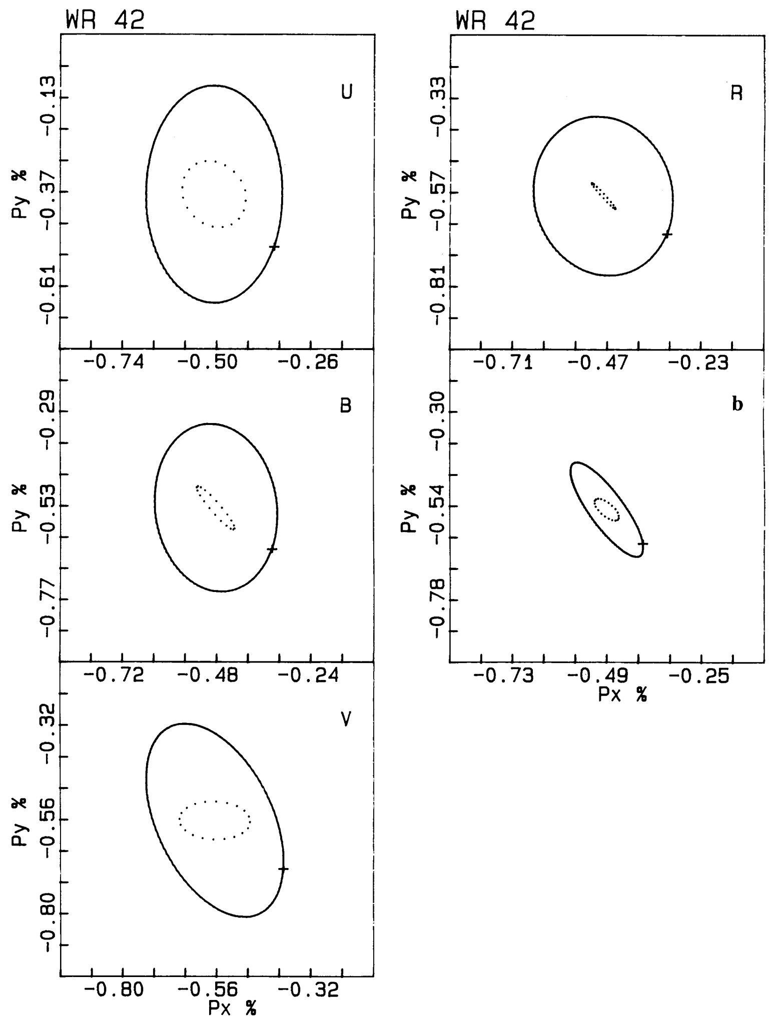

FIG. 2*a*

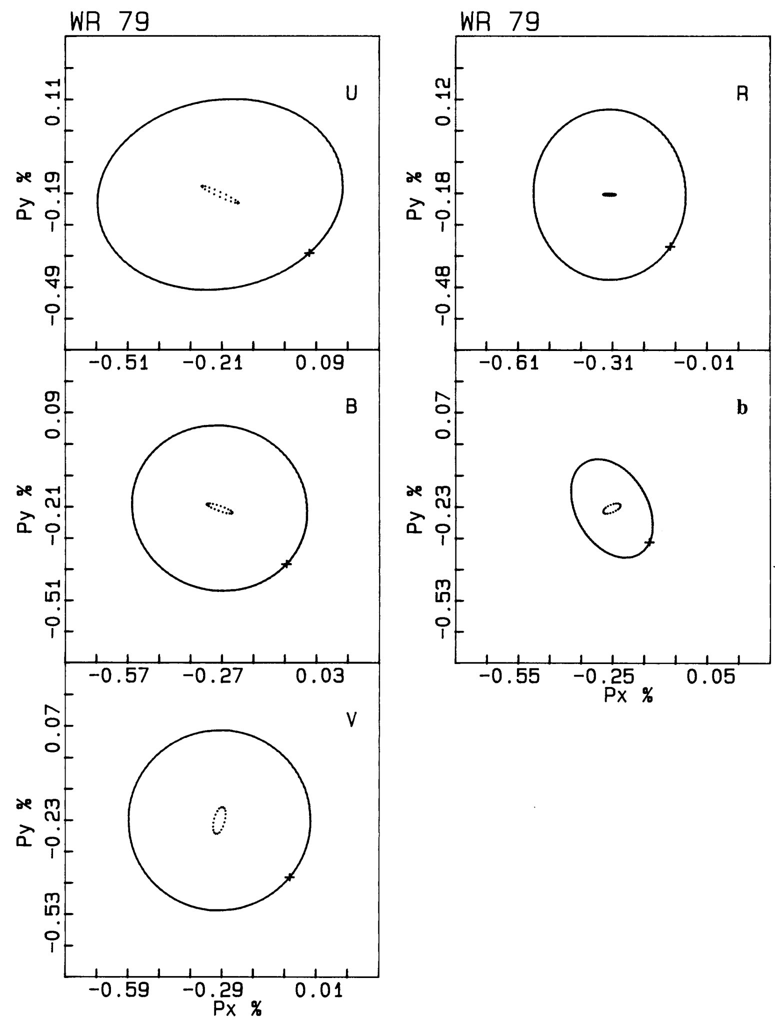

FIG. 2*b*

FIG. 2.—(*a*) Fitted trajectories in the P_x, P_y (or Q, U) plane for WR 42 in different filters. The solid curves (*ellipses*) refer to a second-harmonic fit to the data; the dotted curves (also *ellipses*) refer to a first-harmonic fit to the residuals of the second-harmonic fit. (*b*) As in (*a*), but for WR 79. (*c*) As in (*a*), but for WR 6, except that the curves refer to a *simultaneous* fit using both harmonics.

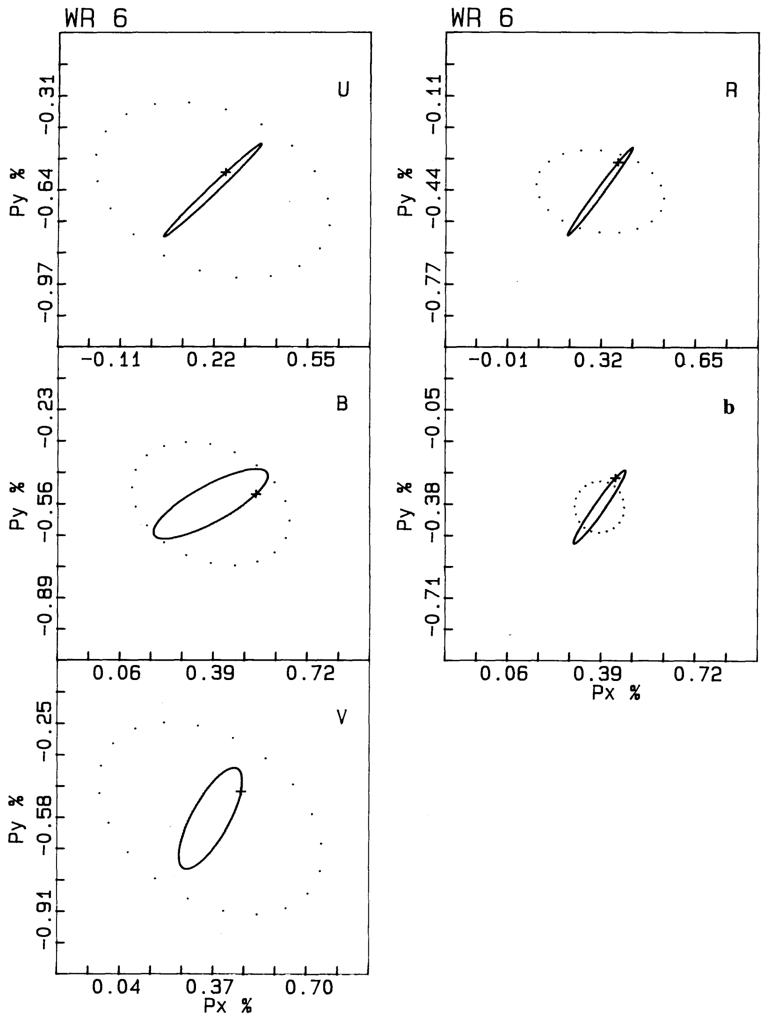

FIG. 2*c*

(e.g., caused by electron scattering; existing optical spectropolarimetry of WR 6 by McLean et al. 1979 and Schulte-Ladbeck et al. 1991 already supports this assumption at most epochs) and an interstellar term, following the well-known empirical Serkowski law (see Serkowski, Mathewson, & Ford 1975), modified more recently by Wilking et al. (1980) and Whittet et al. (1992), and allowing for a (commonly seen) linear inverse wavelength dependent rotation of the interstellar polarization:

$$q_0' \text{ or } q_0(\text{WR } 6) = q_{00} + P_{\text{IS}}(\text{max}) \cos(2\theta_{\text{IS}}) \times \exp[-1.7\, \lambda_{\text{max}} \ln^2(\lambda_{\text{max}}/\lambda)] , \quad (21)$$

$$u_0' \text{ or } u_0(\text{WR } 6) = u_{00} + P_{\text{IS}}(\text{max}) \sin(2\theta_{\text{IS}}) \times \exp[-1.7\, \lambda_{\text{max}} \ln^2(\lambda_{\text{max}}/\lambda)] , \quad (22)$$

where

$$\theta_{\text{IS}} = \theta_{\text{IS}}(0) + k/\lambda . \quad (23)$$

We then fit q_0, u_0, or q_0', u_0', allowing for their uncertainties, versus λ *simultaneously*, with the six free parameters, q_{00}, u_{00}, $P_{\text{IS}}(\text{max})$, $\theta_{\text{IS}}(0)$, k, and λ_{max}. The fitted curves are shown in Figure 4 and the parameters with their errors are listed in Table 4 for each star.

In Figure 4, we see that WR 79 fits well, with normal λ_{max} (550 nm), a small rotation of interstellar polarization, and negligible intrinsic residual polarization (hence a spherically symmetric wind). WR 42, on the other hand, shows unexplainably large scatter in q_0' (U and V filters only: cf. Fig. 1*a*), which renders the solution less certain. Nevertheless, $\lambda_{\text{max}} = 580$ nm and the small rotation of θ_{IS} for WR 42 appear to be normal. Whether the intrinsic polarization is really nonzero or whether the values of q_{00} and u_{00} are spurious in WR 42, cannot be ascertained with these data. Note that for either of these stars, the interstellar polarization based on surrounding field stars at similar distance is relatively chaotic and provides no useful constraints (St-Louis et al. 1987).

We also draw attention to the fact that in Figure 4, the zero point in the narrow b filter fits the curve, within the errors, as well as the broad-band data, for WR 42 and especially WR 79. This can only be so if the mean line polarization is zero, within the errors. This is evident from equations (5) and (6), in which Q, U are taken to be the mean values for each filter, after adjusting for the constant binary term, i.e., q_0', u_0'. Thus, for q, we have the deviations

$$\langle (q_0' - Q_{\text{IS}})_b \rangle = \langle Q_c \rangle/(1 + \alpha_b) + \langle Q_l \rangle/(1 + 1/\alpha_b) , \quad (24)$$

$$\langle (q_0' - Q_{\text{IS}})_B \rangle = \langle Q_c \rangle/(1 + \alpha_B) + \langle Q_l \rangle/(1 + 1/\alpha_B) . \quad (25)$$

TABLE 2A

FITTED FOURIER COEFFICIENTS FOR WR 42 AND WR 79

Filter	Parameter	q_0/u_0		M.E.	q_3/u_3		M.E.	q_4/u_4		M.E.	a_2		M.E.
					WR 42								
U	P_x	−0.502%	±	0.009%	0.152%	±	0.011%	0.084%	±	0.014%	0.347%	±	0.024%
	P_y	−0.397	±	0.009	−0.134	±	0.011	0.242	±	0.014	0.553	±	0.027
B	P_x	−0.470	±	0.007	0.144	±	0.009	0.064	±	0.011	0.314	±	0.019
	P_y	−0.548	±	0.007	−0.105	±	0.010	0.187	±	0.012	0.428	±	0.023
V	P_x	−0.572	±	0.013	0.176	±	0.013	0.013	±	0.022	0.352	±	0.026
	P_y	−0.573	±	0.011	−0.124	±	0.015	0.213	±	0.019	0.493	±	0.036
R	P_x	−0.472	±	0.008	0.162	±	0.011	0.073	±	0.013	0.354	±	0.023
	P_y	−0.587	±	0.007	−0.097	±	0.009	0.178	±	0.011	0.405	±	0.021
b	P_x	−0.482	±	0.011	0.091	±	0.015	−0.014	±	0.018	0.184	±	0.030
	P_y	−0.554	±	0.011	−0.087	±	0.015	0.083	±	0.018	0.241	±	0.033
					WR 79								
U	P_x	−0.217	±	0.009	0.248	±	0.012	−0.269	±	0.013	0.782	±	0.025
	P_y	−0.195	±	0.007	−0.187	±	0.009	−0.241	±	0.010	0.610	±	0.019
B	P_x	−0.272	±	0.007	0.212	±	0.009	−0.179	±	0.010	0.554	±	0.019
	P_y	−0.217	±	0.006	−0.178	±	0.008	−0.197	±	0.009	0.530	±	0.017
V	P_x	−0.300	±	0.015	0.024	±	0.020	−0.183	±	0.022	0.577	±	0.042
	P_y	−0.236	±	0.011	−0.181	±	0.015	−0.225	±	0.017	0.578	±	0.032
R	P_x	−0.319	±	0.009	0.192	±	0.012	−0.146	±	0.013	0.482	±	0.025
	P_y	−0.185	±	0.007	−0.167	±	0.009	−0.217	±	0.010	0.547	±	0.019
b	P_x	−0.255	±	0.009	0.119	±	0.011	−0.053	±	0.013	0.259	±	0.023
	P_y	−0.234	±	0.008	−0.108	±	0.010	−0.115	±	0.012	0.314	±	0.022

NOTE.—a_2 is the peak-to-peak amplitude of the second harmonic term.

TABLE 2B

FITTED FOURIER COEFFICIENTS FOR WR 6

Filter	Parameter	q_0/u_0	q_1/u_1	q_2/u_2	q_3/u_3	q_4/u_4	a_1	a_2	a_{rot}	a_p
U	P_x	0.236	0.096	−0.407	0.043	−0.162	0.836	0.334	1.014	1.025
	P_y	−0.632	−0.304	0.018	0.064	−0.158	0.609	0.341	0.811	
B	P_x	0.381	0.087	−0.265	0.159	−0.122	0.558	0.401	0.830	0.830
	P_y	−0.560	−0.216	−0.009	0.036	−0.118	0.432	0.247	0.586	
V	P_x	0.361	0.163	−0.359	0.106	−0.031	0.788	0.221	0.876	0.883
	P_y	−0.584	−0.337	−0.015	0.096	−0.151	0.675	0.358	0.882	
R	P_x	0.315	−0.002	−0.225	0.061	−0.096	0.450	0.227	0.575	0.602
	P_y	−0.445	−0.145	0.024	0.101	−0.116	0.294	0.308	0.504	
b	P_x	0.385	0.025	−0.084	0.055	−0.073	0.175	0.183	0.315	0.432
	P_y	−0.390	−0.086	−0.026	0.101	−0.080	0.180	0.258	0.390	

NOTE.—a_1 and a_2 are the peak-to-peak amplitudes of the first and second harmonic terms, respectively; a_{tot} is the peak-to-peak amplitude of the combined fit with first and second harmonics; and a_p is the maximum distance between any two points in the combined loop of first and second harmonics in the (P_x, P_y)-plane.

Then, for $\langle(q_0' - Q_{IS})_b\rangle \approx \langle(q_0' - Q_{IS})_B\rangle$ from Figures 4*a* and 4*b*, we find

$$\langle Q_c\rangle[1/(1+\alpha_b) - 1/(1+\alpha_B)] + \langle Q_l\rangle[1/(1+1/\alpha_b) - 1/(1+1/\alpha_B)] = 0 . \quad (26)$$

Since the factors in square brackets are nonzero and unrelated to $\langle Q_c\rangle$, $\langle Q_l\rangle$, this condition implies $\langle Q_c\rangle \approx 0$, $\langle Q_l\rangle \approx 0$. The same holds for the U components.

For WR 6, not only is there a significant offset (i.e., nonzero q_{00}, u_{00}), implying strong intrinsic polarization of the continuum, but the offset in B and especially in b, is large, implying a small but nonzero level of residual polarization in the strong emission line(s) of that star. This result for WR 6 is compatible with that found in general for the same star by Schulte-Ladbeck et al. (1990, 1991), allowing for its high degree of time variability.

4. DISCUSSION

As expected for WR + O binaries, the emission-line flux in WR 42 and WR 79 is intrinsically virtually unpolarized, with any possible amplitude below the instrumental 0.05% level, compared to 0.7% in the continuum. This difference cannot be due, e.g., to the emission lines forming outside the system, since these lines do reflect the WR star orbital motion in each star, and in any case, the free electrons associated with the line-forming region do modulate the continuum polarization

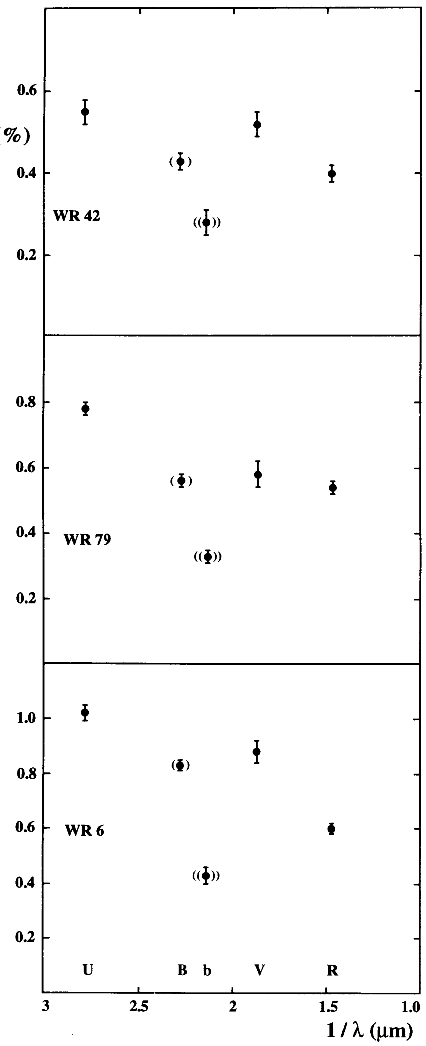

FIG. 3.—Full amplitude a_P (i.e., maximum separation of two points) in the P_x, P_y plane, vs. inverse wavelength for WR 42, WR 79, and WR 6. Two sigma error bars are shown.

TABLE 3

PEAK-TO-PEAK POLARIZATION AMPLITUDES OF VARIABLE COMPONENTS AT $\lambda \approx 460$ nm

	WR 42	WR 79	WR 6
QUANTITY	WC7 + O7V	WC7 + O5–8	WN5
α_b	2.19	1.86	1.97
α_B	0.50	0.52	0.67
ΔQ_c (%)	0.43 ± 0.05	0.79 ± 0.04	1.62 ± 0.10
ΔQ_B(obs) (%)	0.31 ± 0.02	0.55 ± 0.02	0.83 ± 0.03
ΔQ_b(obs) (%)	0.18 ± 0.03	0.26 ± 0.02	0.32 ± 0.04
ΔQ_l (%)	+0.06 ± 0.06	−0.03 ± 0.04	−0.34 ± 0.10
ΔU_c (%)	0.61 ± 0.05	0.71 ± 0.04	0.90 ± 0.10
ΔU_B(obs) (%)	0.43 ± 0.02	0.53 ± 0.02	0.59 ± 0.03
ΔU_b(obs) (%)	0.24 ± 0.03	0.31 ± 0.02	0.39 ± 0.04
ΔU_l (%)	+0.07 ± 0.06	+0.09 ± 0.04	+0.13 ± 0.10

NOTE.—Errors in ΔQ's and ΔU's are lower limits, since they assume that α_b and α_B are error-free. Also, while ΔQ_B, ΔU_B, and ΔQ_b, ΔU_b are observed quantities, ΔQ_c, ΔU_c, and ΔQ_l, ΔU_l are deduced.

TABLE 4

FITTED PARAMETERS TO THE INTERSTELLAR LAW

Parameter	WR 42	WR 79	WR 6
q_{00} (%)	−0.36 ± 0.11	+0.14 ± 0.12	−0.50 ± 0.25
u_{00} (%)	+0.32 ± 0.10	+0.15 ± 0.11	+0.49 ± 0.22
P_{IS}(max) (%)	−0.97 ± 0.10	−0.58 ± 0.12	−1.41 ± 0.24
$\theta_{IS}(0)$	43°9 ± 2°6	15°8 ± 5°2	69°8 ± 5°7
k (° μm)	−0.8 ± 0.6	+5.0 ± 1.3	−3.0 ± 0.6
λ_{max}(nm)	580 ± 9	550 ± 23	457 ± 15

clearly as a function of orbital phase. Future improvements in quantifying the emission-line polarization will require high-precision, phase-dependent spectropolarimetry. Nevertheless, the null emission-line polarization is compatible with the model assumptions mentioned in § 1. In particular, it suggests that the O star winds must be at least an order of magnitude weaker than the WR winds. This is entirely compatible with other independent observations of $\dot{M}$'s for WR and O winds (Prinja, Barlow, & Howarth 1991).

In the case of WR 6, a low level of variability in line polarization at first suggests that WR 6 may be behaving like a binary. However, the nonzero offset in polarization level between the b and B filters, which contain different proportions of emission-line flux, is quite different compared to the two WR + O binaries. Indeed, a previous intense run on WR 6 simultaneously in spectroscopy and continuum polarimetry and photometry is explainable by some kind of obliquely rotating arms or jets protruding from a single WR star (Matthews et al. 1993).

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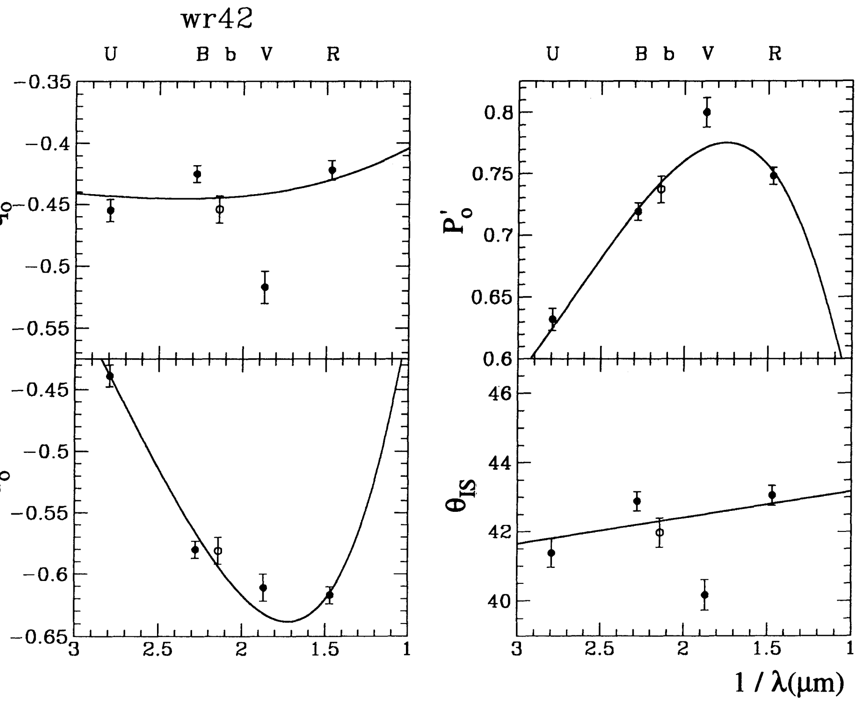

FIG. 4*a*

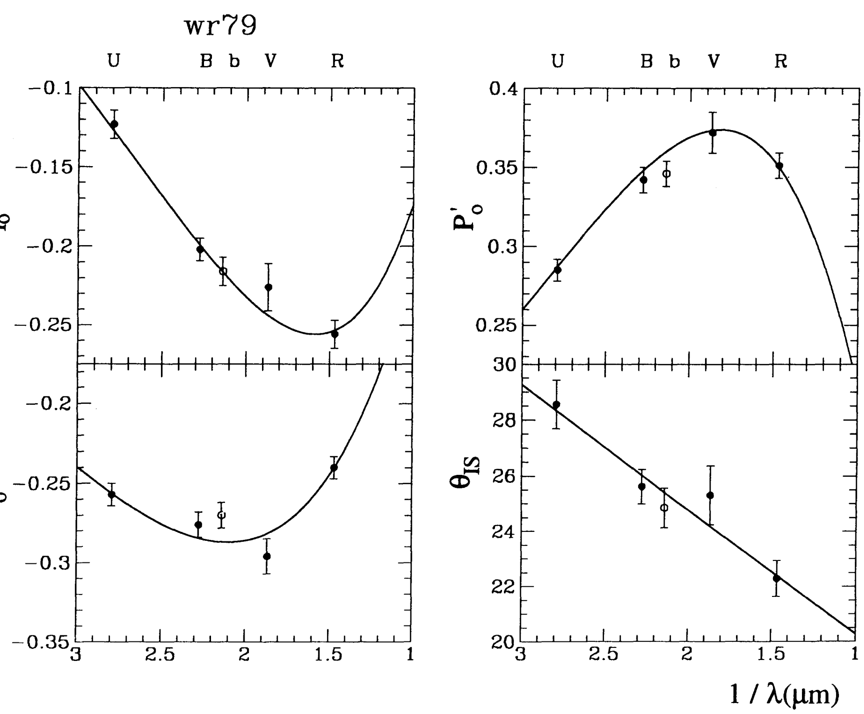

FIG. 4*b*

FIG. 4.—(*a*) Simultaneous interstellar and intrinsic polarization fits with inverse wavelength to the mean polarization in each broad-band pass for WR 42 (cf. eqs. [21], [22], and [23] in text). Two sigma error bars are shown. The data in the *b*-filter are shown but were not included in the fit. Note that $P_0'^2 = q_0'^2 + u_0'^2$. (*b*) As in (*a*), but for WR 79. (*c*) As in (*a*), but for WR 6 and omitting the *b*- and *B*-band data, which are affected by depolarization in the strong emission line(s).

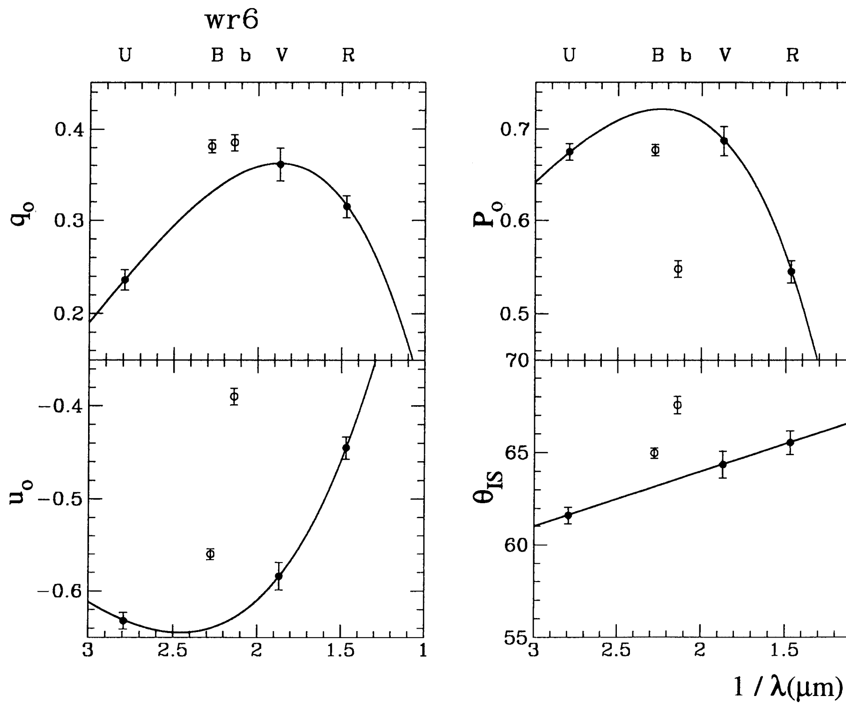

FIG. 4c

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