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POLARIZATION VARIABILITY AMONG WOLF-RAYET STARS. II. LINEAR POLARIZATION OF A COMPLETE SAMPLE OF SOUTHERN GALACTIC WN STARS

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ABSTRACT

We present linear polarization data for the six brightest southern Wolf-Rayet (W-R) stars of the nitrogen sequence (WN), neglecting the peculiar WN 5 star HD 50896, which will be presented elsewhere. They are all of the cool WN 7, WN 8 subclasses, and all show intrinsic, apparently random, variations with amplitudes ranging from $\Delta P = 0.15\%$ to 0.6%. The variations are probably caused by blobs of dense plasma being ejected in the wind. Combining these data with similar results for the seven brightest southern WC stars (Paper I), we find a general anticorrelation between the terminal velocity of the wind and the amplitude of the polarimetric variations. WC 9 and especially WN 8 stars show the largest amplitudes and thus have the least homogeneous winds. No obvious binary-type modulation is detected in the well-known, long-period, single-line WN 7(+O) binary HD 92740 nor in the WN 8 stars suspected of harboring compact companions, HD 86161 and HD 96548. From multicolor polarimetry, we find that the ratio of total visual to selective $B-V$ extinction for three WNL stars in the Carina Nebula is normal, $R = 3.0 \pm 0.2$.

Subject headings: polarization — stars: binaries — stars: winds — stars: Wolf-Rayet

I. INTRODUCTION

In the first paper of this series dealing with polarimetry of southern Wolf-Rayet (W-R) stars (St-Louis *et al.* 1987, hereafter Paper I), we reported variations in the linear polarization of the seven brightest ($b \leq 9$ mag) southern WC stars. The largest full amplitudes ($\Delta P \approx 0.4\%$–0.6%) were detected in binary systems of relatively short period ($P \leq 10$ days). The long-period binaries containing a supergiant showed moderate amplitudes ($\Delta P \sim 0.2\%$) partly due to binary modulation and partly intrinsic to the supergiant star. The two early-subtype single-line WC stars in our sample proved to be almost constant in polarization, while the late-type, WC 9 star varied apparently randomly in time, with a full amplitude $\Delta P \sim 0.3\%$.

In this paper, we investigate the case of the southern, bright WN stars, i.e., W-R stars of the nitrogen sequence with $b \leq 9$ mag. Since there is only one early-type WN star in our sample (HD 50896, WN 5) and since this star shows unusual behavior, we will discuss it elsewhere (Robert *et al.* 1987*a*) and limit this paper to the remaining six WN stars, which all happen to be of the cool, late-type (WNL) subclasses, WN 7 and WN 8. It is well known that the WNL stars form a very special group among W-R stars. The main observational facts that set them apart are the following (see Moffat and Seggewis 1979):

1. Their intrinsic luminosities are typically about two full magnitudes brighter than those of other W-R stars ($M_v \sim -6$ vs. -4), although their bolometric magnitudes may be more similar.
2. Their mean age (measured from the time of their arrival on the ZAMS to the present) is about half that of the other subtypes.
3. Their spectral features are normally narrower than for the other W-R stars.
4. The H/He ratio by number is ≥ 1 for the WNL stars, while it is ≤ 0.15 for the remaining WN subclasses.
5. The ionization structure of their envelopes is different.
6. They are at least twice as massive as the other W-R subtypes (see Lamontagne 1983; Niemela 1983).

These observations suggest that WNL stars possibly form the evolutionary link between the most massive Of stars and the other W-R subtypes (see Conti 1976).

Two relatively bright northern WNL stars have been previously monitored for polarimetric variations. They were chosen initially because of their binary nature: HD 197406 (= WR 148, WN 7 + c; see Drissen *et al.* 1986*a*) and CQ Cep (= WR 155, WN 7 + O; cf. Drissen *et al.* 1986*b*) ("c" stands for compact companion, while the WR numbers are from the catalog of van der Hucht *et al.* 1981). The main variations in these two systems are due to orbital motion, which produces a double-wave modulation per orbital cycle with a relatively large amplitude ($\Delta P = 0.35\%$ for WR 148 and 0.8% for CQ Cep). However, the scatter around the predicted curve in each case is significantly greater than the instrumental scatter. Polarization observations of binary stars have been used to find the inclination of the orbital plane and moments over the electron density in the binary envelope. A brief review of this technique which has been developed during the past 10 years can be found in the introduction of Paper I.

II. OBSERVATIONS AND RESULTS

All the observations presented here were obtained during a continuous 42 night run in 1986 February–April with the Minipol polarimeter of the University of Arizona attached to the University of Toronto 61 cm telescope on Las Campanas, Chile. They were carried out with a wide-band (FWHM = 1800 Å), blue Corning filter centered at 4700 Å. Paper I gives more details on the observational procedure. Table 1 presents an overview of the six stars analyzed in this paper. We give the spectral type, the magnitude, the mean values for P and θ (the position angle of the polarization vector in the equatorial system), the rms scatter in P around the mean [$\sigma(P)$], the color excess E_{B-V}, and the mean interstellar polarization in the region surrounding the star (see Paper I for

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TABLE 1

General Information for the Six WN Stars

HD	WR Name	Spectral Type	b (mag)	$\bar{P}$	$\sigma(P)$	$\bar{\theta}$	E_{B-V}	$\bar{P}_{is}$	σP_{is}	$\bar{\theta}_{is}$	$\sigma\bar{\theta}_{is}$	Number of Stars	Radius
92740	WR 22	WN 7 (+O)	6.5	1.942%	0.043%	102°.9	0.36	1.586%	0.104%	113°.3	1°.9	40	2°
93131	WR 24	WN 7	6.4	2.227	0.045	116.5	0.24	1.356	0.119	112.2	2.5	32	2
93162	WR 25	WN 7	8.5	6.334	0.032	133.6	0.68	1.342	0.103	112.7	2.2	43	2
151932	WR 78	WN 7	6.8	0.961	0.046	36.0	0.52	0.570	0.085	44.4	4.2	36	2
86161	WR 16	WN 8	8.7	1.787	0.080	109.1	0.67	1.414	0.152	130.4	3.1	22	4
96548	WR 40	WN 8	8.0	1.183	0.155	116.7	0.50	0.910	0.072	103.8	2.5	36	4

more details). Figure 1 shows maps of the interstellar polarization in 5° × 5° regions around each star.

a) WN 7 Stars

i) *HD 92740 (= WR 22), WN 7 (+O)*

HD 92740 is a long-period, single-line spectroscopic binary with an eccentric orbit ($P = 80.35$ days, $e = 0.6$; see Moffat and Seggewiss 1978; Conti, Niemela, and Walborn 1979), located in the Great Carina Nebula. Its light curve shows small, nonperiodic changes ($\Delta m \leq 0.04$ mag), although its color index and emission-line strength remain virtually constant. There is no sign of an occultation at phase 0.5, when the W-R star is behind, limiting the orbital inclination to $i \leq 70°$. No photometric data are available at phase 0.0 for this long-period system. A plot of Q versus U (not presented here) shows a completely random character suggesting a lack of a preferred axis or plane for the variations.

TABLE 2

Linear Polarization Data for the WN 7 Star HD 92740 = WR 22

Julian date (2 446 000+)	P(%)	σ_p(%)	θ(°)	σ_θ(°)	Q(%)	U(%)
486.690	1.926	0.013	102.9	0.1	-1.734	-0.838
487.634	1.910	0.007	103.2	0.1	-1.711	-0.849
488.605	1.941	0.015	105.2	0.2	-1.674	-0.982
489.691	1.947	0.010	103.7	0.1	-1.729	-0.896
490.685	1.913	0.011	103.2	0.1	-1.713	-0.851
491.660	1.919	0.009	102.7	0.1	-1.734	-0.823
492.642	1.932	0.008	102.5	0.1	-1.751	-0.816
493.667	1.952	0.014	104.4	0.2	-1.711	-0.940
494.636	1.967	0.011	103.8	0.1	-1.743	-0.911
495.650	1.908	0.008	102.9	0.1	-1.718	-0.830
496.647	1.937	0.010	101.9	0.1	-1.772	-0.782
497.644	2.025	0.010	102.2	0.1	-1.844	-0.837
498.645	1.987	0.007	103.4	0.1	-1.774	-0.896
499.644	1.992	0.007	102.9	0.1	-1.793	-0.867
500.689	1.923	0.009	102.9	0.1	-1.731	-0.837
501.681	1.947	0.009	102.8	0.1	-1.756	-0.841
502.677	1.924	0.004	102.9	0.0	-1.732	-0.837
503.688	1.913	0.010	102.9	0.1	-1.722	-0.833
505.606	1.933	0.008	102.9	0.1	-1.740	-0.841
506.596	1.837	0.012	103.4	0.1	-1.640	-0.828
507.622	1.931	0.010	101.9	0.1	-1.767	-0.779
508.664	2.005	0.009	103.1	0.1	-1.799	-0.885
509.687	1.977	0.013	102.4	0.1	-1.795	-0.829
510.673	1.948	0.011	102.6	0.1	-1.763	-0.829
511.694	1.915	0.007	102.5	0.1	-1.736	-0.809
512.663	1.961	0.012	103.4	0.1	-1.750	-0.884
514.663	1.891	0.012	102.4	0.1	-1.717	-0.793
516.651	1.989	0.012	103.5	0.1	-1.772	-0.903
518.642	1.960	0.006	103.1	0.0	-1.759	-0.865
519.649	1.966	0.008	102.9	0.1	-1.770	-0.856
521.635	1.984	0.012	103.9	0.1	-1.755	-0.925
522.647	1.903	0.013	102.3	0.1	-1.730	-0.792
524.642	1.949	0.012	101.6	0.1	-1.790	-0.767
525.634	1.887	0.009	103.4	0.1	-1.684	-0.851
526.625	1.995	0.009	101.1	0.1	-1.847	-0.754
527.599	1.934	0.015	102.8	0.2	-1.744	-0.836

The polarimetric data are presented in Table 2, and plotted against Julian Date in Figure 2. In Table 2, and in the following similar tables, column (1) refers to the Julian Date of observation; columns (2) and (3) the degree of linear polarization P and its mean error, σ_p; columns (4) and (5) the position angle, θ, in the equatorial system and its mean error, σ_θ; columns (6) and (7) the Stokes parameters $Q = P \cos 2\theta$ and $U = P \sin 2\theta$. The quoted error σ_θ is a rms error. The estimated systematic error on our position angles lies between 0°.3 and 0°.5 and corresponds to the accuracy with which the standard polarized stars are known (Hsu and Breger 1982; Bastien *et al.* 1987.) A period-search routine following the parameter-free technique of Lafler and Kinman (1965) was applied to these data, but no significant period was found. The amplitude of the variations is low, but statistically significant ($\Delta P \approx 0.15\% \approx 10\ \sigma$, where σ is the estimated instrumental scatter). The typical time scale of the variations lies around 1–4 days. There is no evidence for a long-term modulation related to the orbital motion, which is not surprising in view of (*a*) the large separation between the two components and (*b*) the relative faintness of the secondary O-type star, which is the main source of asymmetry relative to the free electrons in the W-R wind, capable of producing a phase-dependent modulation of the polarization. The variations are more likely to be related to inhomogeneities in the W-R wind itself.

ii) *HD 93131 (= WR 24) and HD 93162 (= WR 25)*

Like HD 93740, both these stars are located in the Carina Nebula. They were claimed to be single stars by Moffat and Seggewiss (1978), Moffat (1978), and Conti, Niemela, and Walborn (1979). No significant periodic variations in radial velocities (RV) were observed, and both stars are constant in brightness, color, and line strength (within the respective instrumental accuracies).

HD 93162 is one of the intrinsically brightest known X-ray emitters among W-R stars [L_x(0.5–4 keV) = 7.4×10^{33} ergs s^{-1}] and the second brightest X-ray source in the Carina Nebula, after η Car itself ($L_x = 12 \times 10^{33}$ ergs s^{-1}; see Seward and Chlebowski 1982). L_x/L_{bol} for this star is ~30 times higher than for the two other bright W-R stars in this area, HD 92740 and HD 93131.

The polarization data for WR 24 and WR 25 are listed in Tables 3 and 4, and plotted against Julian Date in Figures 3 and 4, respectively. The variations for both stars are similar in character to the polarization variations seen in WR 22, and likewise, no significant periodicity has been found. Plots in the

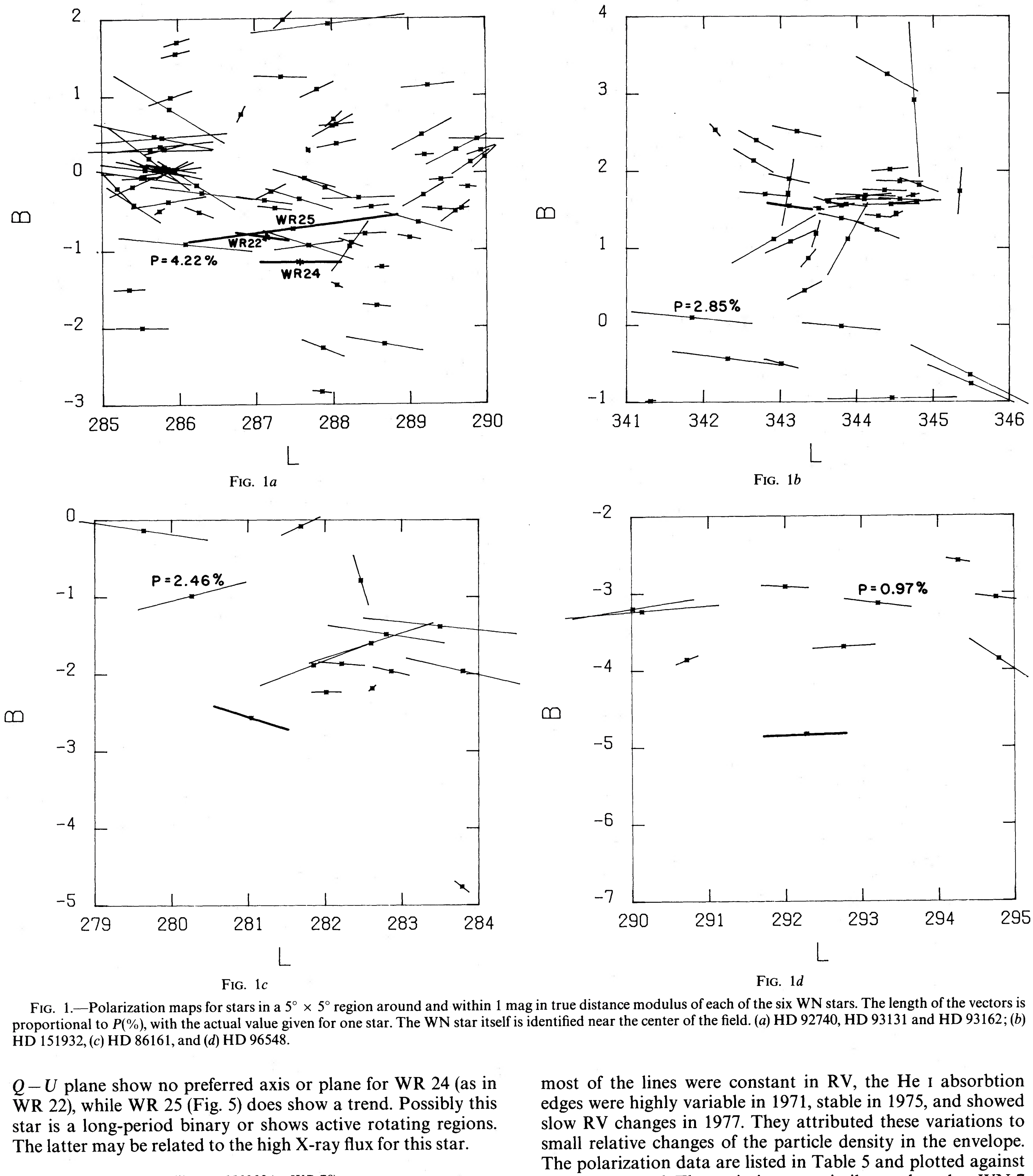

FIG. 1*a* FIG. 1*b* FIG. 1*c* FIG. 1*d*

FIG. 1.—Polarization maps for stars in a 5° × 5° region around and within 1 mag in true distance modulus of each of the six WN stars. The length of the vectors is proportional to *P*(%), with the actual value given for one star. The WN star itself is identified near the center of the field. (*a*) HD 92740, HD 93131 and HD 93162; (*b*) HD 151932, (*c*) HD 86161, and (*d*) HD 96548.

$Q-U$ plane show no preferred axis or plane for WR 24 (as in WR 22), while WR 25 (Fig. 5) does show a trend. Possibly this star is a long-period binary or shows active rotating regions. The latter may be related to the high X-ray flux for this star.

iii) *HD 151932* (= *WR 78*)

Spectroscopy and photometry led Seggewiss and Moffat (1979) to conclude that the WN 7 star HD 151932, located near the young open cluster NGC 6231 in the core of the association Sco OB1, is probably single. They found that, although most of the lines were constant in RV, the He I absorbtion edges were highly variable in 1971, stable in 1975, and showed slow RV changes in 1977. They attributed these variations to small relative changes of the particle density in the envelope. The polarization data are listed in Table 5 and plotted against time in Figure 6. The variations are similar to the other WN 7 stars, and no significant periodicity has been found. The polarization vector for this star is fairly well aligned with that of other stars in the area, indicating that a large fraction of this star's polarization is interstellar. As in the case of WR 22 and

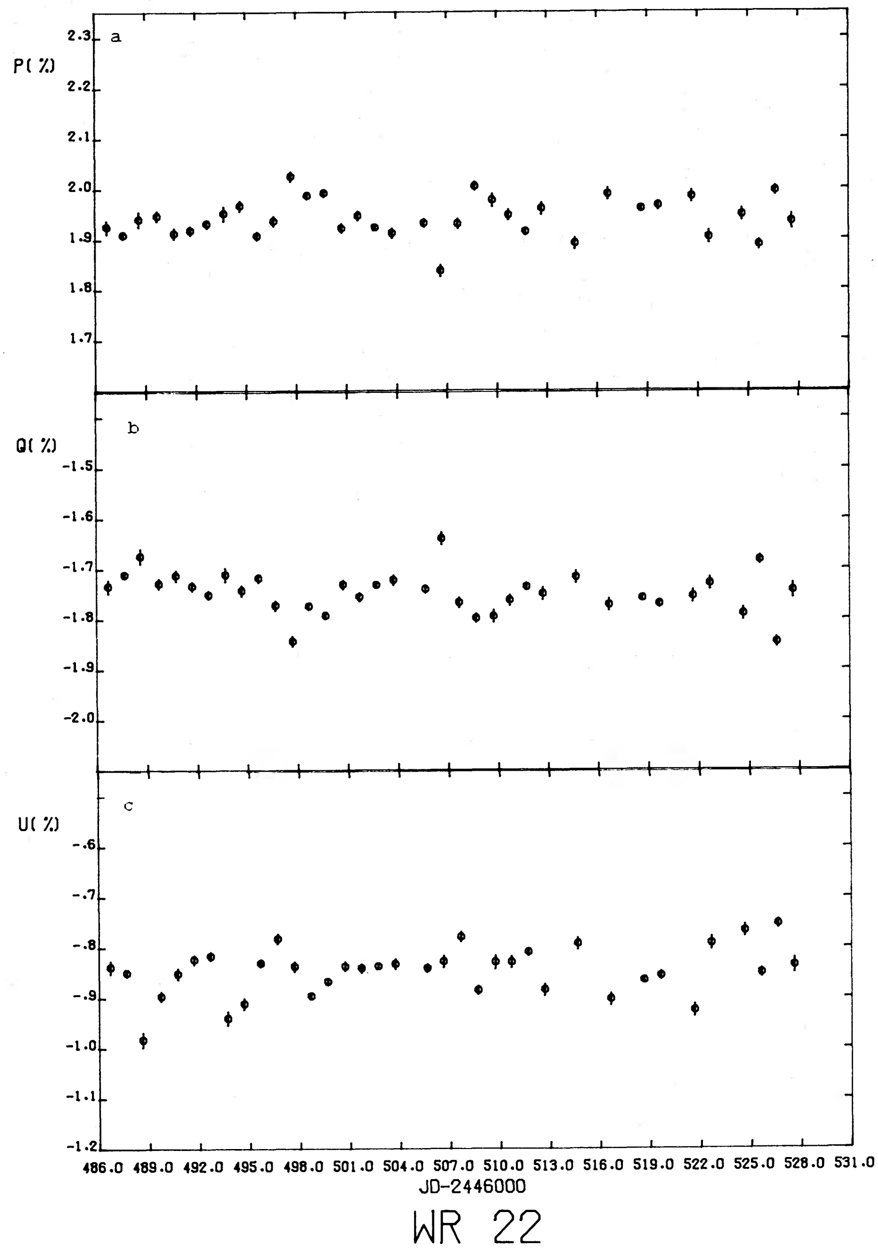

FIG. 2.—Stokes parameters Q and U as well as P, plotted as a function of Julian Date for WR 22 = HD 92740, WN 7(+O). Error bars here and throughout the figures refer to 2 σ estimates.

WR 24, WR 78 shows only stochastic variability in the $Q-U$ plane (Fig. 7), implying the lack of a preferred axis or plane.

b) Polarization and Extinction in the Carina Nebula

The extinction law in the direction of the Carina Nebula has been the object of many investigations, often in contradiction with one another. Herbst (1976) found $R = A_V/E_{B-V} = 5$. Thé, Bakker, and Tjin A. Djie (1980) found $R = 3.89 \pm 0.1$ from the photometry of 14 O-type stars. Turner and Moffat (1980) presented *UBV* photometry and deduced a more normal value of $R = 3.20 \pm 0.28$ for this region.

Serkowski, Mathewson, and Ford (1975, hereafter SMF) established a general correlation between λ_{max}, the wavelength at which the maximum interstellar polarization P_{max} occurs, and the value of R: $R = 5.5\lambda_{max}(\mu m)$. According to them, polarimetry seems to be the most effective method of estimating R. Whittet and van Breda (1978) found $R = (5.6 \pm 0.3)\lambda_{max}(\mu m)$ from a larger number of stars.

In addition to the data with our broad-band Corning blue filter, we have measured the linear polarization of the three Carina WN 7 stars with U and I filters (and R filter for WR 22) on one occasion (see Table 6). Assuming that the intrinsic polarization of each star is negligible compared to the interstellar component, we have fitted the data to the empirical interstellar polarization law (SMF):

$$P(\lambda) = P_{max} \exp\left[-K \ln^2 (\lambda_{max}/\lambda)\right] ,$$

where K was initially defined to be a constant = 1.15 by SMF and was later found to be better represented by $K = 1.7\lambda_{max}$ by Wilking *et al.* (1980). The fits are slightly better with $K = 1.15$,

TABLE 3

LINEAR POLARIZATION DATA FOR THE WN 7 STAR HD 93131 = WR 24

Julian date (2 446 000+)	P(%)	σ_p(%)	θ(°)	σ_θ(°)	Q(%)	U(%)
486.708	2.240	0.012	115.9	0.1	-1.385	-1.760
487.648	2.209	0.013	116.9	0.1	-1.305	-1.783
488.613	2.279	0.010	117.4	0.1	-1.314	-1.862
489.728	2.305	0.010	116.4	0.1	-1.394	-1.836
490.698	2.274	0.009	117.5	0.1	-1.304	-1.863
491.671	2.184	0.009	117.4	0.1	-1.259	-1.785
492.653	2.255	0.013	116.9	0.1	-1.332	-1.820
493.676	2.218	0.014	117.3	0.1	-1.285	-1.808
494.647	2.170	0.008	117.4	0.1	-1.251	-1.773
495.659	2.231	0.009	117.4	0.1	-1.286	-1.823
496.659	2.240	0.008	117.3	0.1	-1.298	-1.826
497.652	2.197	0.010	116.9	0.1	-1.298	-1.773
498.654	2.132	0.010	116.2	0.1	-1.301	-1.689
499.653	2.217	0.006	116.1	0.0	-1.359	-1.752
500.701	2.221	0.008	115.9	0.1	-1.373	-1.745
501.692	2.220	0.011	115.3	0.1	-1.409	-1.715
502.688	2.229	0.008	115.8	0.1	-1.385	-1.747
503.699	2.140	0.009	116.6	0.1	-1.282	-1.714
505.615	2.211	0.010	116.1	0.1	-1.355	-1.747
506.602	2.228	0.011	116.2	0.1	-1.359	-1.765
507.631	2.241	0.011	116.5	0.1	-1.349	-1.790
508.673	2.166	0.010	115.1	0.1	-1.386	-1.664
509.695	2.264	0.012	115.7	0.1	-1.412	-1.769
510.683	2.277	0.009	116.4	0.1	-1.377	-1.814
511.702	2.248	0.012	115.9	0.1	-1.390	-1.767
512.672	2.226	0.008	116.1	0.1	-1.364	-1.759
513.673	2.222	0.009	116.3	0.1	-1.350	-1.765
514.672	2.196	0.011	116.1	0.1	-1.346	-1.735
516.663	2.228	0.009	117.3	0.1	-1.291	-1.816
518.650	2.254	0.006	116.4	0.0	-1.363	-1.795
519.656	2.195	0.011	116.8	0.1	-1.303	-1.767
521.643	2.205	0.012	117.1	0.1	-1.290	-1.788
522.672	2.297	0.006	116.5	0.0	-1.382	-1.834
524.651	2.224	0.013	116.7	0.1	-1.326	-1.785
525.641	2.198	0.013	116.9	0.1	-1.298	-1.774
526.631	2.230	0.011	116.8	0.1	-1.323	-1.795
527.659	2.313	0.010	115.7	0.1	-1.443	-1.808

TABLE 4

LINEAR POLARIZATION DATA FOR THE WN 7 STAR HD 93162 = WR 25

Julian date (2 446 000+)	P(%)	σ_p(%)	θ(°)	σ_θ(°)	Q(%)	U(%)
486.735	6.275	0.025	133.5	0.1	-0.328	-6.266
487.663	6.330	0.017	133.9	0.0	-0.243	-6.325
488.628	6.299	0.018	133.8	0.0	-0.264	-6.293
489.742	6.414	0.018	133.6	0.0	-0.313	-6.406
490.763	6.356	0.022	134.1	0.1	-0.200	-6.353
491.698	6.396	0.016	133.7	0.0	-0.290	-6.389
492.667	6.345	0.017	134.1	0.0	-0.199	-6.342
493.706	6.312	0.015	133.9	0.0	-0.242	-6.307
494.658	6.371	0.012	134.3	0.0	-0.156	-6.369
495.673	6.286	0.016	133.9	0.0	-0.241	-6.281
496.674	6.337	0.013	133.9	0.0	-0.243	-6.332
497.664	6.396	0.016	133.8	0.0	-0.268	-6.390
498.667	6.373	0.016	133.6	0.0	-0.311	-6.365
499.667	6.346	0.015	133.7	0.0	-0.288	-6.339
500.713	6.318	0.019	132.8	0.0	-0.485	-6.299
501.702	6.350	0.020	132.8	0.0	-0.487	-6.331
502.698	6.335	0.015	133.4	0.0	-0.354	-6.325
503.716	6.329	0.023	133.4	0.1	-0.353	-6.319
505.630	6.342	0.020	133.5	0.0	-0.332	-6.333
506.617	6.336	0.018	133.2	0.0	-0.398	-6.323
507.642	6.330	0.020	133.3	0.0	-0.375	-6.319
508.688	6.323	0.020	133.5	0.0	-0.331	-6.314
509.706	6.313	0.012	133.3	0.0	-0.374	-6.302
510.692	6.263	0.016	133.2	0.0	-0.393	-6.251
512.683	6.321	0.019	133.6	0.0	-0.309	-6.313
513.683	6.345	0.012	133.7	0.0	-0.288	-6.338
516.676	6.339	0.014	133.4	0.0	-0.354	-6.329
518.660	6.342	0.018	133.7	0.0	-0.288	-6.335
519.667	6.319	0.022	133.9	0.1	-0.243	-6.314
521.654	6.326	0.016	133.7	0.0	-0.287	-6.319
523.626	6.327	0.015	133.7	0.0	-0.287	-6.320
524.660	6.346	0.017	133.6	0.0	-0.310	-6.338
525.651	6.339	0.018	133.6	0.0	-0.310	-6.331
526.644	6.323	0.013	133.6	0.0	-0.309	-6.315

TABLE 5

LINEAR POLARIZATION DATA FOR THE WN 7 STAR 151932 = WR 78

Julian date (2 446 000+)	P(%)	σ_p(%)	θ(°)	σ_θ(°)	Q(%)	U(%)
486.818	0.949	0.011	36.2	0.3	0.287	0.905
487.803	0.919	0.015	38.6	0.4	0.204	0.896
488.826	1.037	0.012	34.4	0.3	0.375	0.967
489.830	0.902	0.010	34.9	0.3	0.311	0.847
490.848	0.925	0.011	40.1	0.3	0.157	0.912
491.842	0.889	0.012	36.3	0.3	0.266	0.848
492.854	0.847	0.013	35.8	0.4	0.267	0.804
493.836	1.018	0.012	35.3	0.3	0.338	0.960
494.828	0.977	0.010	34.0	0.2	0.366	0.906
495.840	0.921	0.008	35.2	0.2	0.309	0.868
496.811	0.925	0.010	33.9	0.3	0.350	0.856
497.815	0.996	0.009	35.7	0.2	0.318	0.944
498.807	0.962	0.009	36.4	0.2	0.284	0.919
499.829	1.025	0.009	35.5	0.2	0.334	0.969
500.820	0.971	0.009	35.4	0.2	0.319	0.917
501.849	0.932	0.011	36.1	0.3	0.285	0.887
503.808	0.972	0.009	36.1	0.2	0.297	0.925
504.809	0.943	0.010	34.5	0.3	0.338	0.880
505.826	0.960	0.011	34.8	0.3	0.335	0.900
506.837	0.923	0.011	36.1	0.3	0.282	0.879
507.812	0.952	0.008	36.4	0.2	0.282	0.909
508.810	0.916	0.018	35.8	0.5	0.289	0.869
509.803	0.965	0.011	34.0	0.3	0.361	0.895
510.821	0.962	0.009	37.7	0.2	0.242	0.931
511.845	0.939	0.012	36.8	0.3	0.265	0.901
512.811	1.016	0.013	36.1	0.3	0.311	0.967
513.781	1.049	0.011	37.7	0.3	0.264	1.015
516.828	0.964	0.014	36.2	0.4	0.291	0.919
517.746	0.989	0.012	35.5	0.3	0.322	0.935
518.783	1.024	0.012	35.9	0.3	0.320	0.973
519.826	1.000	0.012	35.3	0.3	0.332	0.943
521.808	0.953	0.012	34.6	0.3	0.338	0.891
522.818	0.915	0.008	35.2	0.2	0.307	0.862
523.856	1.067	0.013	35.0	0.3	0.365	1.003
524.813	1.004	0.010	37.3	0.2	0.267	0.968
526.875	0.950	0.010	38.1	0.3	0.227	0.923
527.797	0.958	0.014	38.5	0.4	0.216	0.933

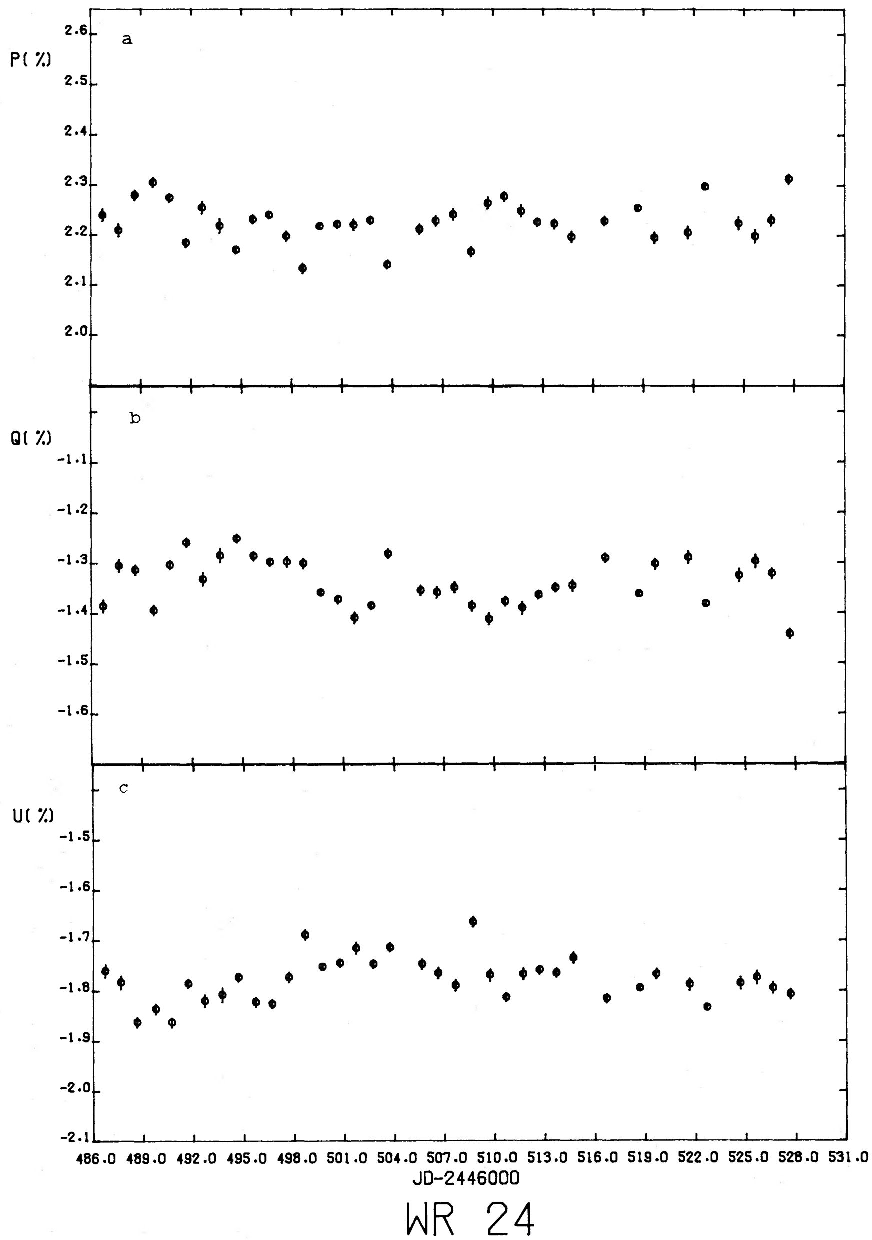

FIG. 3

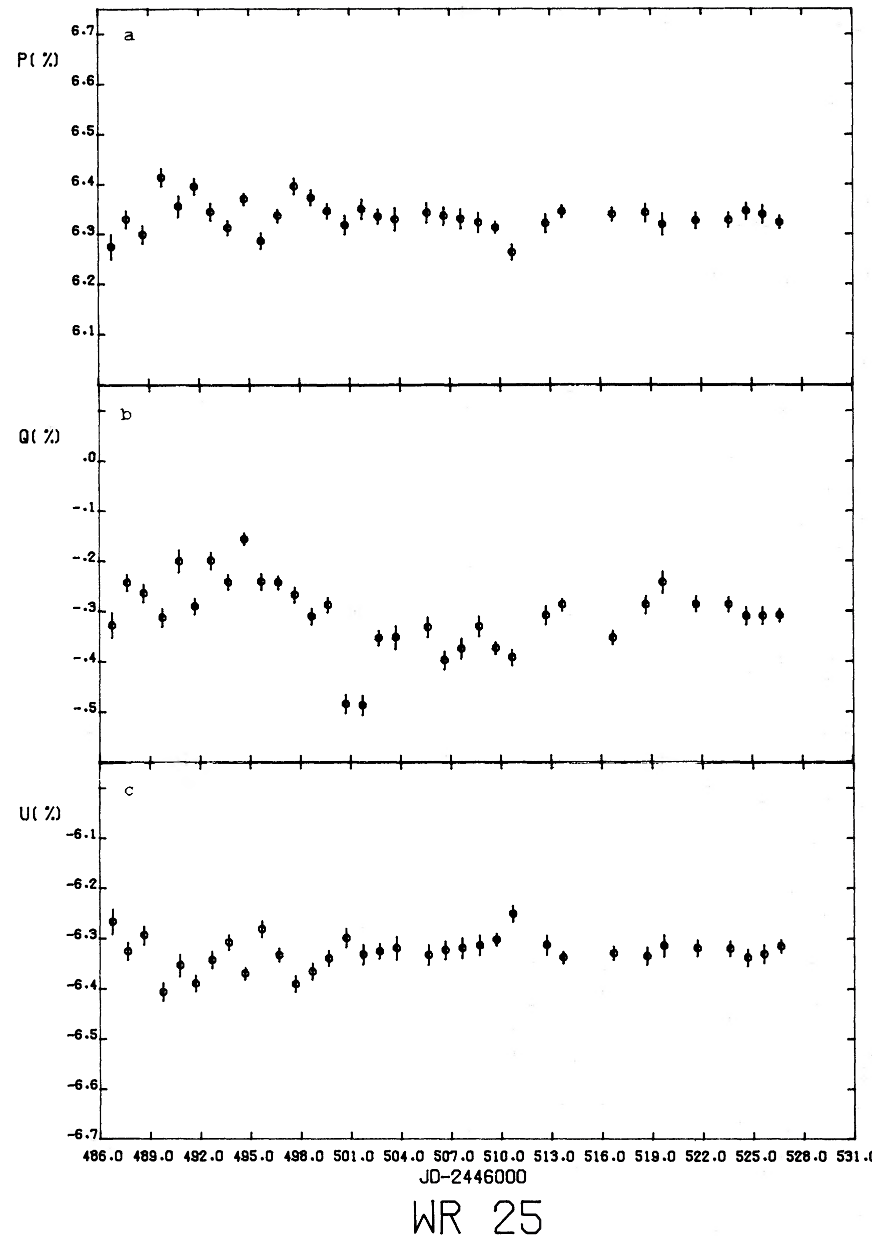

FIG. 4

FIG. 3.—Same as Fig. 2, for WR 24 = HD 93131, WN 7
FIG. 4.—Same as Fig. 2, for WR 25 = HD 93162, WN 7

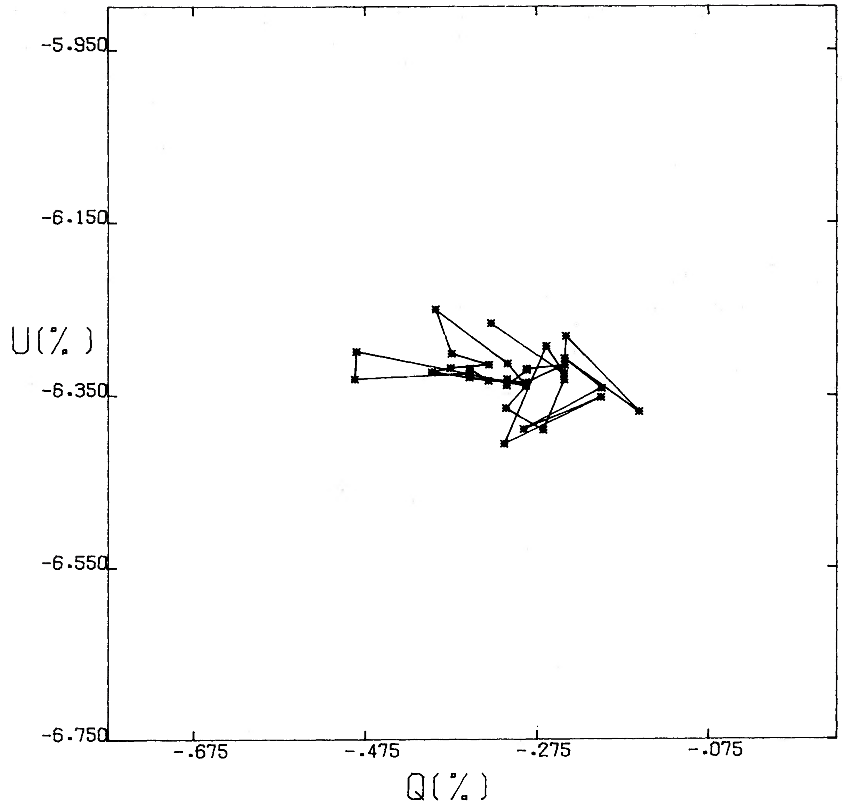

FIG. 5.—Polarimetric variations for HD 93162 = WR 25 in the (Q, U)-plane

which we adopt here, but the values of P_{max} and λ_{max} are only marginally different from their values based on fits with $K = 1.7\lambda_{max}$. The fit is in excellent agreement with the observations for WR 22 and WR 24, but less satisfactory in the case of WR 25 (see Fig. 8). As we can see from Table 1, the position angles of the polarization vector for WR 22 and WR 24 are fairly well aligned with the mean interstellar value (within 11° and 4°, respectively), while WR 25 differs both in P and θ (21° away from the mean). The values of λ_{max} and P_{max} for each star obtained from the fit are listed in Table 6, along with the value of R deduced from λ_{max}. The average value, $R = 3.01 \pm 0.14(\sigma)$, is normal and is in agreement with the result of Turner and Moffat (1980). With a more extended data base, SMF found $\lambda_{max} = 5700$ Å ($R = 3.14$) for WR 22 and $\lambda_{max} = 5400$ Å ($R = 2.97$) for WR 24. To get even $R = 4$ would require $\lambda_{max} =$ 7300 Å, which is clearly ruled out by the polarimetry. Although our sample is not large enough to generalize to the whole area of the Carina Nebula, a normal R-value is clearly indicated in parts of it.

It is worth noting the very high value of P_{max}/E_{B-V} for WR 24 and WR 25 (9.8 and 10.2, respectively; see Table 6). Even if we adopt the average value of the polarization in the blue band filter, $P = 6.34\%$ for WR 25 as P_{max}, the ratio P_{max}/E_{B-V} is still quite high, i.e., 9.3. This ratio rarely exceeds 9.0 (SMF). The efficiency of grain alignment in this region of the nebula should then be very high to explain the observed ratio, and in the case of WR 25 it is tempting to suggest the presence of an intrinsic polarization component, like a circumstellar shell, to account for the high degree of polarization and the fact that the observations are not well reproduced by a fit to the SMF relation.

TABLE 6

MULTIBAND OBSERVATIONS OF CARINA W-R STARS

		U FILTER		4700 FILTER		*R* FILTER		*I* FILTER						
STAR	JD (−2,446,000)	P ($\pm\sigma_P$)	θ	P ($\pm\sigma_P$)	θ	P ($\pm\sigma_P$)	θ	P ($\pm\sigma_P$)	θ	E_{B-V}	λ_{max} (Å)	P_{max}	R	P_{max}/E_{B-V}
WR 22	522.64	1.62% (0.01)	102°7	1.90% (0.01)	102°3	1.93% (0.02)	100°7	1.76% (0.02)	100°0	0.36	5570	2.02%	3.06	5.6
WR 24	522.67	1.99 (0.02)	115.4	2.30 (0.01)	116.5			1.91 (0.03)	115.3	0.24	5192	2.35	2.86	9.8
WR 25	523.63	5.58 (0.06)	133.3	6.33 (0.02)	133.7			6.21 (0.02)	136.1	0.68	5683	6.95	3.12	10.2

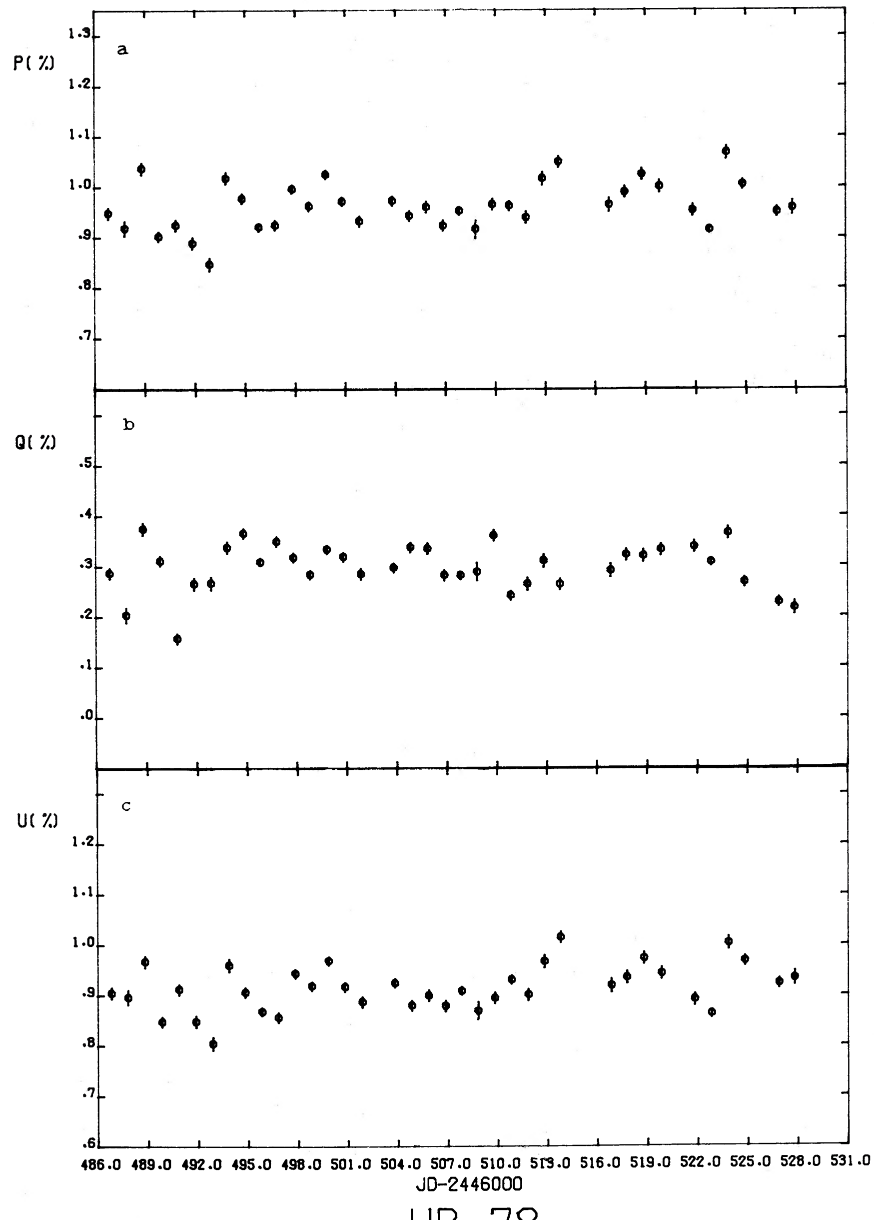

FIG. 6.—Same as Fig. 2, for WR 78 = HD 151932, WN 7

c) *WN 8 Stars*

The polarization vectors of the two WN 8 stars are more or less aligned with those of the stars around them, but the number of stars is too small to conclude anything on the presence of an intrinsic polarization component in the WN 8 stars.

i) *HD 86161* (= *WR 16*)

Moffat and Niemela (1982) claimed a periodicity ($P = 10.73$ days) in the light curves and the spectroscopic data of this star and suggested that it was a binary system with an unseen companion of probable mass 0.5–1.2 $M_{\odot}$. Lamontagne and Moffat (1987) confirm the period in their new photometric data. However, the standard deviation from the light curve is relatively large, and the amplitude of the RV variations is very low ($K = 4.7 \pm 2.8$ km s^{-1} for N IV λ4058 and 7.2 ± 2.4 km s^{-1} for Hδ, the two best observed emission lines).

The polarimetric observations (Table 7 and Fig. 9) were obtained with a 6″ diaphragm (compared to the usual diaphragm of 10″) to avoid the light from a close visual companion (separation = 8″, 3.5 mag fainter). Application of a period-search routine failed to reveal any *convincing* period from these data. The time scale for variations is very similar to the WN 7 stars, but the amplitude is definitely larger. A plot of Q versus U in Figure 10 suggests the existence of a mildly preferred axis, e.g., a binary seen near face-on or a single rotating star seen near pole-on. Nevertheless, any systematic effect like this seems to be masked by stochastic variability when it comes to a search for periodicity.

ii) *HD 96548* (= *WR 40*)

HD 96548 has been known to be strongly variable in light, ever since the first few repeated observations of Smith (1968),

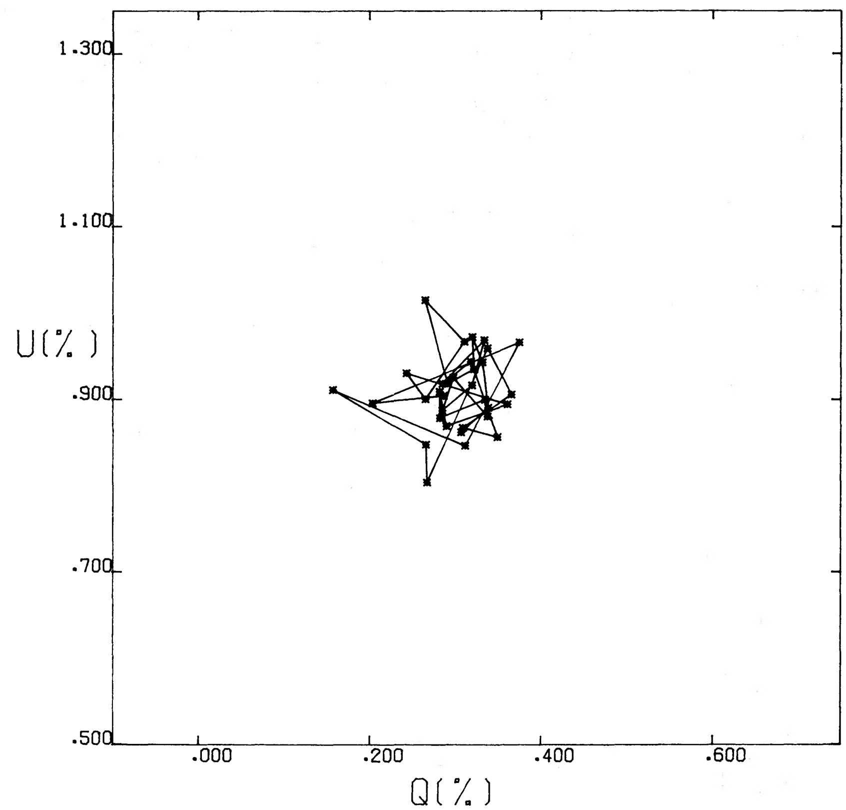

FIG. 7.—Polarimetric variations for HD 151932 = WR 78 in the (*Q*, *U*)-plane

and is one of the 10 galactic Population I WN stars associated with a clear ring-shaped nebulosity (Chu 1980). Extensive narrow-band photometry (Moffat and Isserstedt 1980) shows two kinds of variations: random noise of ~0.02 mag on a time scale of days and a claimed periodic modulation ($P = 4.76$ days) with a full amplitude of 0.04 mag. Moffat (1983) revised this period to $P = 4.16$ days on the basis of all combined radial velocity data, although several other periods between 4 and 5 days are also possible, including one near 4.8 days. More recently, Lamontagne and Moffat (1987) find $P = 4.7$ days as best period in their extensive photometry of this star. Smith, Lloyd, and Walker (1985) obtained a limited quantity of new visible photometric and UV spectroscopic data. They found that their photometry combined with previous data was periodic ($P = 5.879$ days or its 1 day aliases, 0.855 and 1.204 days), but, although dramatic changes were observed in the UV line profiles, the corresponding RV changes were not periodic. Both teams suggested that a compact companion may be the cause of the periodic modulations, although the latter authors also allow an alternative explanation, i.e., due to the effects of nonradial pulsations.

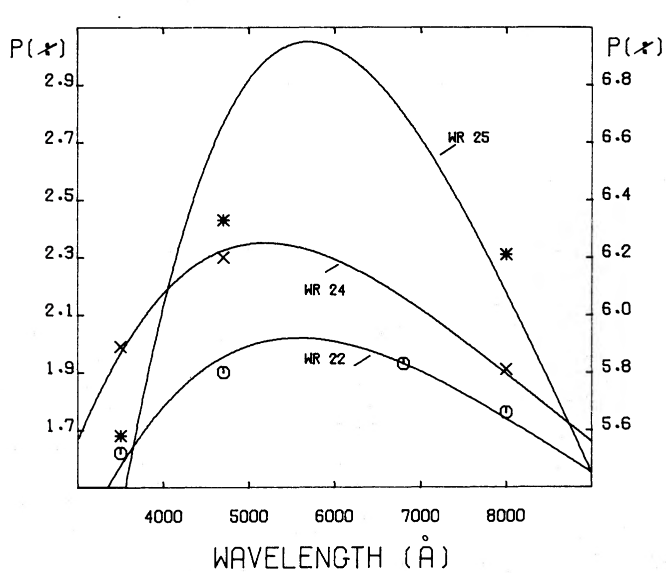

FIG. 8.—Polarization as a function of wavelength for the three Carina W-R stars. Solid lines represent a fit to the interstellar polarization law (see text). The left scale refers to WR 22 and WR 24; the right scale refers to WR 25. *Circles*, WR 22; *crosses*, WR 24; *asterisks*, WR 25.

Our polarimetric observations (Table 8, Fig. 11), obtained typically with a frequency of two measurements per night and sometimes with additional observations in a red filter (not shown in Fig. 11), show dramatic variations of very large amplitude ($\Delta P \approx 0.6\%$). As in the case of the other WNL stars presented in this paper, no convincing periodicity was found. Plotting the data (*P*, *Q*, or *U*) using any of the periods previously claimed results in a scatter diagram. Although at times the polarization was nearly constant during a given night, changes of $\Delta P \approx 0.1\%$ and/or $\Delta\theta \geq 2°$ within a few hours occur frequently. This kind of fluctuation is very similar to the case of P Cygni, the prototype rapidly mass-losing supergiant (Hayes 1985). The amplitude is the same for both P Cygni and HD 96548, although the time scale for changes appears to be somewhat longer for P Cygni: for those nights with multiple observations, the variations in P Cyg never exceeded 0.05% (in

TABLE 7

Linear Polarization Data for the WN 8 Star HD 86161 = WR 16

Julian date (2 446 000+)	P(%)	σ_p(%)	θ(°)	σ_θ(°)	Q(%)	U(%)
486.668	1.769	0.017	109.6	0.2	-1.371	-1.118
487.596	1.737	0.017	110.5	0.2	-1.311	-1.140
488.577	1.758	0.017	109.5	0.4	-1.366	-1.106
489.623	1.765	0.025	113.1	0.4	-1.222	-1.274
490.597	1.827	0.019	107.2	0.2	-1.507	-1.032
491.578	1.728	0.014	109.9	0.2	-1.328	-1.106
492.604	1.836	0.013	109.8	0.2	-1.415	-1.170
493.593	1.906	0.010	110.4	0.1	-1.443	-1.245
494.576	1.912	0.016	109.4	0.2	-1.490	-1.198
495.578	1.826	0.015	107.8	0.2	-1.485	-1.063
496.583	1.769	0.019	109.9	0.3	-1.359	-1.132
497.572	1.736	0.020	110.2	0.3	-1.322	-1.125
498.593	1.811	0.019	107.4	0.3	-1.487	-1.034
499.582	1.712	0.024	108.6	0.4	-1.364	-1.035
500.606	1.754	0.019	108.4	0.3	-1.404	-1.051
501.578	1.728	0.022	107.9	0.3	-1.402	-1.011
502.624	1.882	0.022	109.8	0.3	-1.450	-1.200
503.578	1.734	0.017	109.9	0.2	-1.332	-1.110
504.633	1.784	0.019	108.1	0.3	-1.440	-1.054
505.665	1.717	0.016	109.4	0.2	-1.338	-1.076
506.660	1.822	0.021	106.9	0.3	-1.514	-1.014
507.674	1.965	0.018	109.7	0.2	-1.518	-1.247
509.668	1.891	0.020	109.9	0.3	-1.453	-1.210
510.643	1.777	0.020	108.9	0.3	-1.404	-1.089
511.658	1.728	0.019	107.3	0.3	-1.422	-0.981
512.647	1.789	0.016	109.4	0.2	-1.394	-1.121
513.648	1.838	0.014	106.7	0.2	-1.534	-1.012
514.647	1.738	0.013	109.9	0.2	-1.335	-1.113
516.615	1.863	0.016	110.2	0.2	-1.419	-1.207
517.611	1.761	0.020	109.2	0.3	-1.380	-1.094
518.608	1.579	0.017	109.1	0.3	-1.241	-0.976
519.633	1.726	0.024	109.8	0.3	-1.330	-1.100
521.619	1.767	0.030	108.4	0.4	-1.415	-1.058
522.576	1.866	0.023	110.7	0.3	-1.400	-1.234
523.592	1.700	0.025	108.9	0.4	-1.343	-1.042
525.624	1.838	0.020	106.9	0.3	-1.527	-1.022
526.615	1.943	0.020	110.2	0.2	-1.480	-1.259
527.618	1.694	0.021	110.7	0.3	-1.271	-1.120

P), and the adjacent night-to-night changes were never larger than $\Delta P = 0.2\%$. For the nights with multiple observations, the rate of polarization variations ($\Delta P/\Delta t$, linear extrapolating to a full day) in WR 40 ranges from $-1.2\% \pm 0.2\%$ per day to $+1.1\% \pm 0.3\%$ per day, and the absolute value often exceeds 0.6% per day, which is similar to the total amplitude observed for this star. This is also the case for the WC 9 star WR 103 (see Paper I: $\Delta P/\Delta t$ for the Arizona data ranges from $-0.6\% \pm 0.3\%$ per day to $+1.1\% \pm 0.2\%$ per day, the total amplitude of the variations being 0.3%). Even though a linear extrapolation of the short-term variations may not be entirely realistic, these observations suggest that the time scale for at least some polarimetric variations may be less than 1 day. The variations (both in Q and U for WR 40) are quite coherent in the blue and the red. this is consistent with the hypothesis that the mechanism responsible for the polarization is Thomson scattering by free electrons in an inhomogeneous wind. A plot of Q versus U in Figure 12 shows a completely stochastic nature with a large amplitude. Hence the variations do not appear to be spatially correlated.

III. DISCUSSION

The principal result emerging from the monitoring of the linear polarization of the 13 brightest southern W-R stars (Paper I and this paper, neglecting the peculiar WN 5 object HD 50896) is that most of them show some kind of generally incoherent polarization variability intrinsic to the W-R star. Only two stars, WR 90 and WR 111, both WC, stars, show no significant variability above the instrumental scatter. The two well-known WC + O binaries WR 42 and 79 show very little scatter around the predicted double-wave curve caused by binary motion. These four stars are members of the hotter subtypes, WC 5–7. The variations in the two WC + supergiant systems γ^2 Vel and θ Mus can probably be attributed at least in part to the supergiant companion, so little can be said about the W-R star as intrinsic source in these two cases. These two systems are therefore not included in the following discussion.

All WN 7 stars show similar random fluctuations with amplitude of ~0.2%. The largest amplitudes are seen in the slow-wind late-subtype WC 9 and WN 8 stars.

In Table 9, we have listed the standard deviations [$\sigma(P)$] of the polarization (from the simple average in the case of a single star, and from the predicted curve for the binaries) and the terminal wind velocities v_∞ for the 11 stars observed in this paper and Paper I (we exclude γ^2 Vel and θ Mus). Figure 13 shows a plot of $\sigma(P)$ versus v_∞. Taking into account the uncertainties in the determination of v_∞, Figure 13 reveals a fairly tight correlation in the sense that *the fast-wind stars show less scatter in polarization than the slow-wind stars.* The winds appear therefore to be more stable for WC 5–7 stars and more subject to instabilities for WN 8, WC 9 stars. A similar trend is also observed in photometric variability (Lamontagne and Moffat 1987). There is also a hint of a correlation between the polarimetric variations and the value of $\dot{M}/v_\infty$, measured from the radio flux (Abbott *et al.* 1986). This would mean that the denser the wind is, the more it is subject to polarization variations. Unfortunately, the number of stars for which accurate values of $\dot{M}$ and $\sigma(P)$ are available does not allow us to elaborate further on this hypothesis. We will return to it in a later paper concerning the polarization of the eight W-R stars in Cygnus (Robert *et al.* 1987*b*).

The most plausible explanation for these incoherent variations and their correlation with wind speed is that blobs of dense plasma may form, possibly as a result of nonradial pulsations or instabilities in the line-driven winds (Lucy and Solomon 1970) and be ejected at random directions into the wind at its base. These blobs may be more stable in slow winds: high-speed winds may act as an efficient homogenizing agent, virtually destroying any perturbation that may arise. Lucy and White (1980) have suggested that schocks caused by the movements of blobs in the winds of hot stars may account for their observed X-ray fluxes. However, this model implies that ~10^9 blobs should exist in the wind at any given time, while the polarimetric observations suggest the presence of just one or a few detectable events per day. Nevertheless, since polarimetry is unable to detect spherically symmetric mass loss, the events observed could be due to an asymmetry in the blob production, the ultimate cause of which still remains a mystery. The change in the X-ray production resulting from such an asymmetry ($\Delta P \leq 1\%$) would be too low to be detected. According to our observations, the main difference between the "active" and the "quiet" stars does not seem to be the number of events, but their amplitude. If the blob

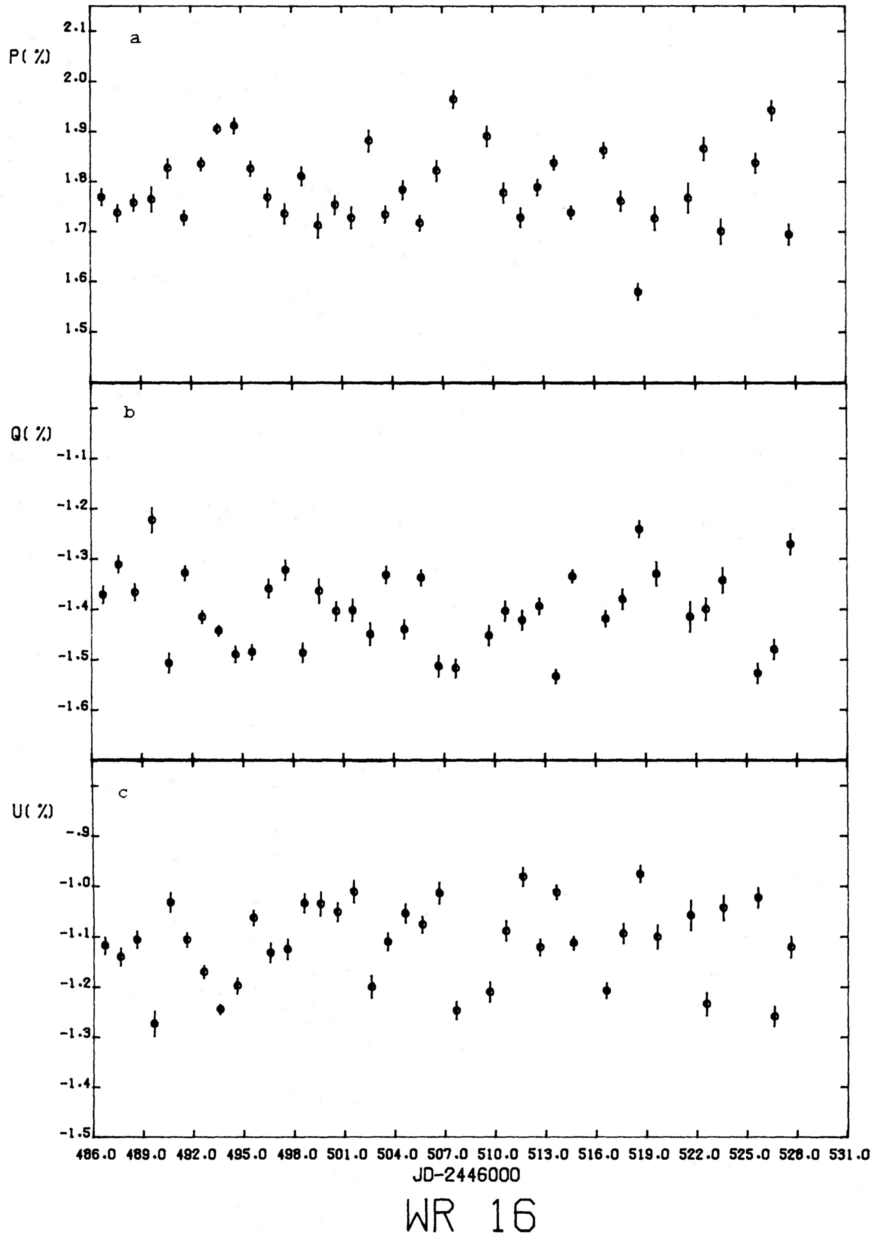

FIG. 9

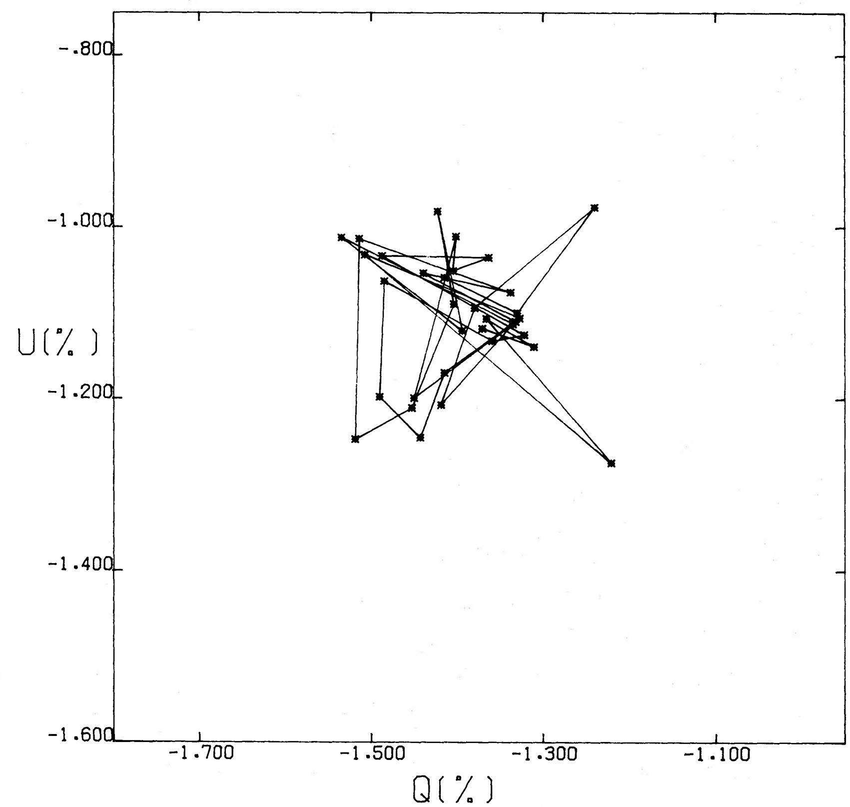

FIG. 10

FIG. 9.—Same as Fig. 2, for WR 16 = HD 86161, WN 8

FIG. 10.—Polarimetric variations for HD 86161 = WR 16 in the (Q, U)-plane

TABLE 8

LINEAR POLARIZATION DATA FOR THE WN 8 STAR HD 96548 = WR 40

Julian date (2 446 000+)	P(%)	σ_p(%)	θ(°)	σ_θ(°)	Q(%)	U(%)	Filter
486.779	1.019	0.020	112.5	0.6	-0.721	-0.721	1
487.684	1.320	0.018	117.6	0.4	-0.753	-1.084	1
488.595	1.042	0.017	111.1	0.5	-0.772	-0.700	1
488.715	1.021	0.017	110.0	0.5	-0.782	-0.656	1
489.705	1.100	0.016	122.8	0.4	-0.454	-1.002	1
490.636	1.251	0.014	113.3	0.3	-0.860	-0.909	1
490.721	1.206	0.015	114.8	0.4	-0.782	-0.918	1
491.598	1.368	0.011	121.7	0.2	-0.613	-1.223	1
491.719	1.277	0.017	121.0	0.4	-0.600	-1.128	1
492.617	1.131	0.018	115.4	0.5	-0.715	-0.876	1
492.698	1.103	0.014	118.3	0.4	-0.607	-0.921	1
493.630	0.835	0.012	113.9	0.4	-0.561	-0.619	1
493.721	0.936	0.016	112.6	0.5	-0.660	-0.664	1
494.610	1.439	0.012	113.7	0.2	-0.974	-1.059	1
494.703	1.343	0.016	112.9	0.3	-0.936	-0.963	1
495.618	1.244	0.013	114.5	0.3	-0.816	-0.939	1
495.702	1.220	0.014	115.9	0.3	-0.754	-0.959	1
496.615	1.177	0.009	121.7	0.2	-0.527	-1.052	1
496.703	1.068	0.013	120.2	0.3	-0.528	-0.929	1
497.607	1.284	0.012	124.4	0.3	-0.464	-1.197	1
497.714	1.280	0.009	127.7	0.2	-0.323	-1.239	1
498.615	1.333	0.011	109.3	0.2	-1.042	-0.832	1
498.706	1.275	0.009	111.8	0.2	-0.923	-0.879	1
499.617	1.329	0.010	114.8	0.2	-0.861	-1.012	1
499.708	1.293	0.012	114.0	0.3	-0.865	-0.961	1
500.635	1.341	0.013	117.9	0.3	-0.754	-1.109	1
500.735	1.418	0.015	116.5	0.3	-0.853	-1.132	1
501.619	1.255	0.012	120.2	0.3	-0.620	-1.091	1
501.731	1.308	0.014	114.5	0.3	-0.858	-0.987	1
502.570	1.156	0.011	123.1	0.3	-0.466	-1.058	1
502.570	1.123	0.007	121.2	0.2	-0.520	-0.995	2
502.734	1.045	0.011	116.7	0.3	-0.623	-0.839	1
502.746	0.965	0.017	116.4	0.5	-0.583	-0.769	2
503.731	1.333	0.012	112.7	0.3	-0.936	-0.949	1
504.676	1.187	0.012	120.7	0.3	-0.568	-1.042	1
504.695	1.144	0.016	117.4	0.4	-0.659	-0.935	2
505.594	1.072	0.013	110.6	0.3	-0.807	-0.706	1
505.714	1.069	0.014	111.4	0.4	-0.784	-0.726	1
506.573	1.303	0.014	115.7	0.3	-0.813	-1.018	1
506.584	1.248	0.012	113.7	0.3	-0.845	-0.919	2
506.694	1.268	0.010	117.2	0.2	-0.738	-1.031	1
507.599	1.048	0.010	116.6	0.3	-0.628	-0.839	1
507.706	1.041	0.014	114.2	0.4	-0.691	-0.778	1
508.708	1.107	0.013	117.8	0.3	-0.625	-0.913	1
509.615	1.045	0.015	123.0	0.4	-0.425	-0.955	1
509.721	1.049	0.019	123.8	0.5	-0.400	-0.970	1
510.587	1.098	0.008	123.7	0.2	-0.422	-1.014	1
510.723	1.098	0.007	125.6	0.2	-0.354	-1.039	1
511.590	1.060	0.012	114.4	0.3	-0.698	-0.798	1
511.681	1.123	0.015	116.5	0.4	-0.676	-0.897	1
512.610	1.035	0.014	113.9	0.4	-0.695	-0.767	1
512.625	1.020	0.014	113.1	0.4	-0.706	-0.736	2
513.619	1.070	0.017	114.8	0.5	-0.693	-0.815	1
514.690	0.972	0.016	114.6	0.5	-0.635	-0.736	1
514.702	0.951	0.021	112.0	0.6	-0.684	-0.661	2
516.555	1.341	0.012	116.4	0.3	-0.811	-1.068	1
516.697	1.318	0.010	114.0	0.2	-0.882	-0.979	1
516.697	1.309	0.015	115.8	0.3	-0.813	-1.026	1
517.564	1.249	0.015	120.0	0.3	-0.624	-1.082	1
517.577	1.222	0.015	116.8	0.4	-0.725	-0.984	2
517.632	1.191	0.014	123.5	0.3	-0.465	-1.096	1
517.644	1.169	0.012	119.4	0.3	-0.606	-1.000	2
517.672	1.211	0.014	124.2	0.3	-0.446	-1.126	1
517.684	1.176	0.009	120.4	0.2	-0.574	-1.027	2
518.555	1.061	0.014	119.9	0.4	-0.534	-0.917	1
518.684	1.188	0.018	118.2	0.4	-0.657	-0.990	1
519.557	1.320	0.011	118.1	0.2	-0.734	-1.097	1
519.680	1.223	0.016	118.1	0.4	-0.680	-1.016	1
521.567	1.204	0.016	114.9	0.4	-0.777	-0.920	1
521.580	1.115	0.015	114.8	0.4	-0.723	-0.849	2
522.636	1.332	0.017	109.5	0.4	-1.035	-0.838	1
523.676	1.233	0.015	117.4	0.3	-0.711	-1.008	1
524.671	1.336	0.014	114.6	0.3	-0.873	-1.011	1
525.544	1.059	0.019	108.5	0.5	-0.846	-0.637	1
525.557	1.080	0.015	109.3	0.4	-0.844	-0.674	2
525.665	1.026	0.008	112.8	0.2	-0.718	-0.733	1
526.661	1.119	0.016	119.4	0.4	-0.580	-0.957	1
526.672	1.162	0.014	118.1	0.3	-0.646	-0.966	2
527.669	1.159	0.014	109.6	0.3	-0.898	-0.733	1

NOTE.—Filter 1 = 4700/1800; filter 2 = *R* filter.

TABLE 9

POLARIZATION SCATTER AND TERMINAL VELOCITY

Star	Spectral Subclass	$\sigma(P)$	v_∞ (km s^{-1})	Source for v_∞
WR 16..........	WN 8	0.080%	1200	4
WR 22..........	WN 7(+O)	0.043	2600	2
WR 24..........	WN 7	0.045	2900	2
WR 25..........	WN 7	0.032	2900	1
WR 40..........	WN 8	0.155	1800	2
WR 42..........	WC 7 + O5–7	0.020	2800	3
WR 78..........	WN 7	0.046	2400	2
WR 79..........	WC 7 + O5–8	0.020	3300	1
WR 90..........	WC 7	0.015	3000	2
WR 103.........	WC 9	0.067	1400	2
WR 111.........	WC 5	0.020	3700	2

SOURCES.—(1) Barlow, Smith, and Willis 1981. (2) Willis 1982. (3) Torres, Conti, and Massey 1986. (4) Average of four WN 8 stars from Abbott *et al.* 1986.

hypothesis is correct, the amplitude of the polarization variations could be modified by the density of the blobs or by the volume of the wind affected by the asymmetry in the blob production.

A few W-R stars have been detected in X-rays (White and Long 1986, and references therein), but there is no obvious correlation between X-ray flux and polarimetric variability.

Our observations do not allow us to determine the cause of the polarization variability among single W-R stars; theoretical calculations of blob production and ejection and their effect on polarization behavior are needed. However, we can say that the asymmetric activity of W-R winds is probably influenced by some combination of its velocity field, its density, and its ionization structure.

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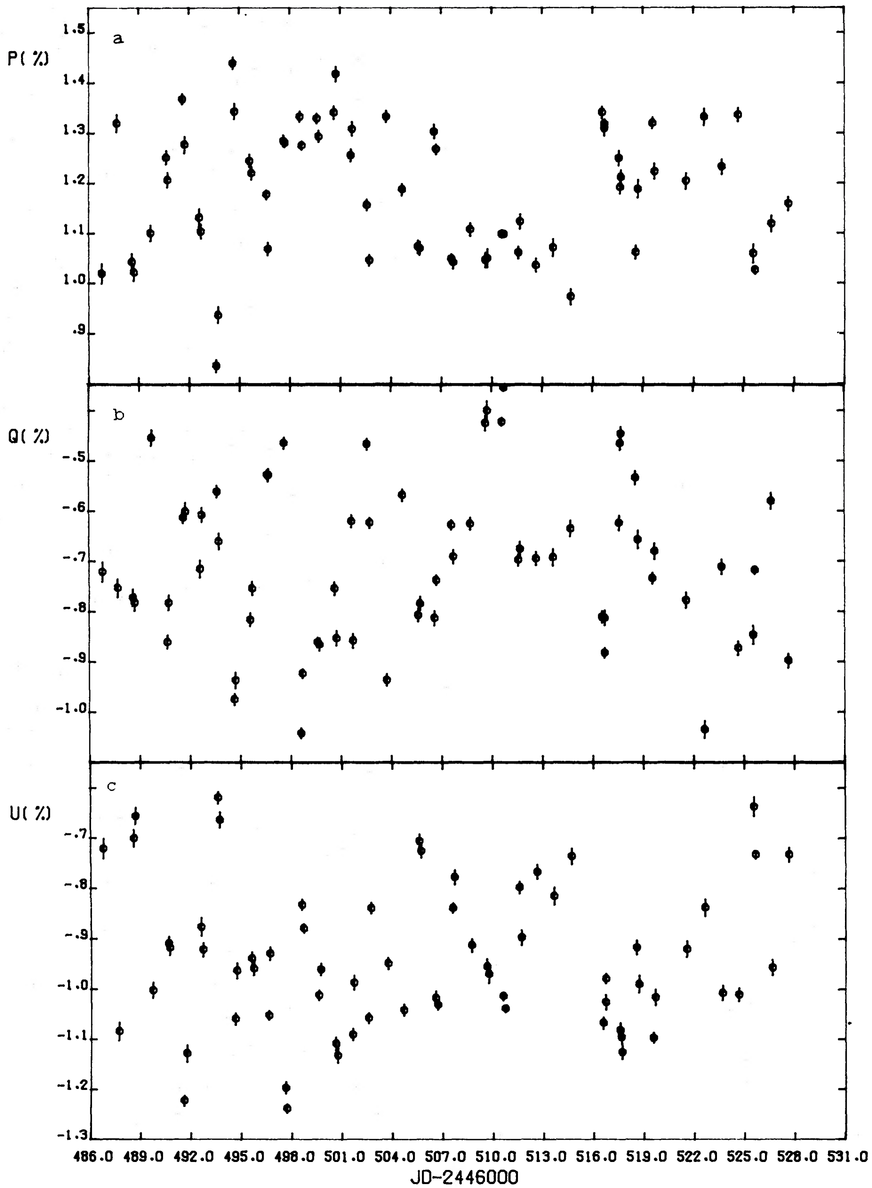

FIG. 11

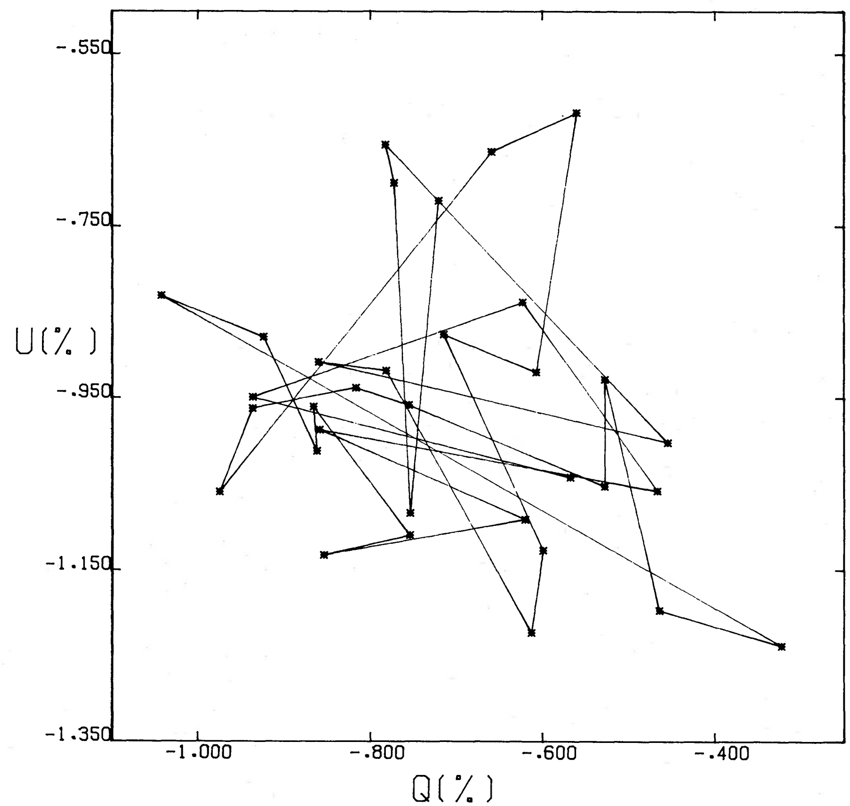

FIG. 12

FIG. 11.—Same as Fig. 2, for WR 40 = HD 96548, WN 8

FIG. 12.—Polarimetric variations for HD 96548 = WR 40 in the (Q, U)-plane

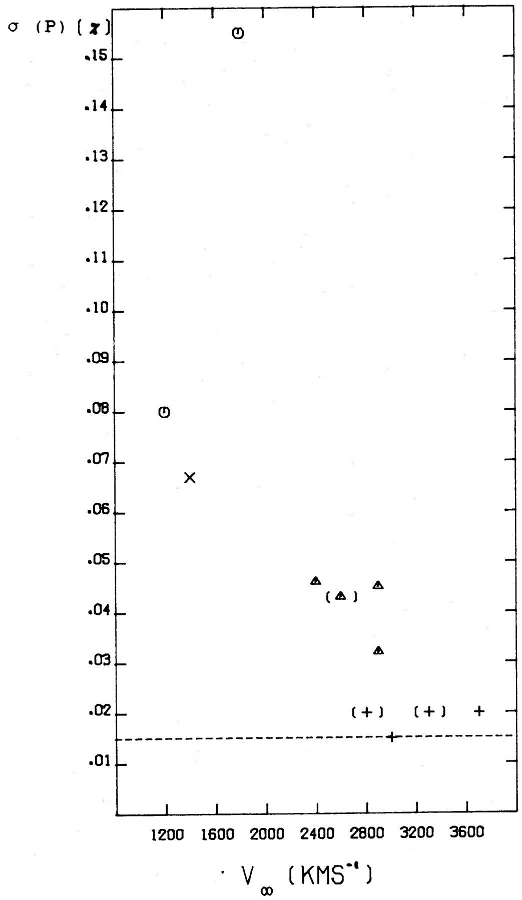

FIG. 13.—Polarization scatter vs. wind terminal velocity for 11 of the brightest southern W-R stars (see Table 9). Parentheses identify binary systems. Circles, WN 8; cross, WC 9; triangles, WN 7; plus signs, WC 5–WC 7. Dotted line corresponds to the value of the mean instrumental scatter.

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