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POLARIZATION VARIABILITY AMONG WOLF-RAYET STARS. V. LINEAR POLARIZATION OF THE BRIGHT CYGNUS STARS AND AN ANTICORRELATION OF VARIABILITY WITH WIND SPEED

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ABSTRACT

We report precision broad-band blue light monitoring in linear polarization of seven of the eight bright Cygnus Wolf-Rayet (WR) stars. The six WR stars HD 191765, HD 192103, HD 192163, HD 192641, HD 193077, and HD 193793, show only random, low-amplitude modulation on time scales of hours to days. HD 190918 behaves as expected for a long-period WR + O system with an elliptical orbit. The eighth star, V444 Cyg (HD 193576), is the only short-period WR + O binary in the Cygnus sample and is treated in detail elsewhere.

The polarization data for the eight bright Cygnus WR stars are combined with similar data for 18 other WR stars of various spectral subtypes. We confirm a previous suspicion that the degree of random, intrinsic scatter in polarization is correlated with spectral subclass and terminal wind velocity. This is proposed to be caused by the presence of propagating blobs, which form, survive, and/or grow more easily in slower winds, especially for WN stars (compared to WC stars).

We develop two models to explain the origin of the blobs. The first model is based on the exponential growth rate predicted by Owocki, Castor, and Rybicki for the amplitude of a radiatively driven line-shape instability. This model leads to a correlation between the polarization scatter and a combination of the terminal and thermal wind velocities, the mass-loss rate, and the stellar core radius. It is not clear if the observations reproduce this correlation, because of uncertainties in the stellar parameters.

Another simpler, but more ad hoc model, which relates the growth rate of the dispersion to the size of the perturbation itself (of unknown origin), yields a correlation between the polarization scatter and the exponential of the wind propagating time. This time is proportional to the WR core radius divided by the terminal wind velocity. This model fits the data better, especially for the WN stars, but is still far from compelling.

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

I. INTRODUCTION

Because of their hot, intense winds, Wolf-Rayet (WR) stars are potential sources of linear polarization via Thomson scattering from their copious number of free electrons. However, net polarization differing from zero can only be observed in the total light from the star as a consequence of *asymmetries* in the relative distribution of the light source(s) and the scatterers.

The first paper of this series (St.-Louis *et al.* 1987; hereafter Paper I) contains good examples of polarimetric behavior of several single WR stars and WR + O binary systems. For the binaries, various parameters are deduced, such as the inclination of the orbital plane, which leads to estimates of the stellar masses. (See Bastien 1989 for a discussion of retograde orbits which were not correctly interpreted at the time of Paper I.) The identification of time-dependent polarimetric variations in single WR stars (Drissen *et al.* 1987; hereafter Paper II) provides a useful new way to investigate intrinsic asymmetries in the WR wind structure. In Paper III, St.-Louis *et al.* (1988) propose a new method, based on the polarization modulation of binaries, to calculate the mass-loss rate ($\dot{M}$) of the WR components.

This paper presents polarimetric data for seven of the eight bright WR stars in Cygnus. Polarimetric data of the WR + O binary V444 Cyg (HD 193576), which shows a polarization eclipse of the scatterers, is treated more extensively in a separate paper (Robert *et al.* 1989; hereafter Paper VI).

With the new polarimetric observations for the eight bright Cygnus WR stars, the overall sample of WR stars monitored so far in high-precision polarimetry is now complete for the whole sky to $V = 9.2$ mag. Furthermore, most of the WR subtypes are now represented.

The observations and a discussion of the reduction procedures for the eight bright Cygnus WR stars, including V444 Cyg, are given in § II. A discussion of individual stars follows in § III. The overall significance of the intrinsic polarimetric variations in the new large sample of objects is the subject of § IV. A summary is given in § V.

II. OBSERVATIONS AND ANALYSIS

The spectral types and the magnitudes of the eight bright Cygnus WR stars are listed in Table 1. These parameters were gathered mainly from the catalog of van der Hucht *et al.* (1981).

Polarimetric data for one object presented here, HD 192163, were first collected in 1984 May and November at three different telescopes: the 1.52 m of Mount Lemmon (Arizona), the 1.55 m of Mount Bigelow (Arizona), and the 1.60 m of Mont Mégantic (Québec). In 1985 October measurements were carried out for the whole sample of stars with the 1.55 m telescope of Mount Bigelow and the 1.02 and 1.52 m telescopes of Mount Lemmon. The observations were then completed during another visit to the 1.02 m telescope of Mount Lemmon in 1986 October. Most of the observations were made with the

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TABLE 1

General Information for the Eight Bright Cygnus WR Stars

HD	WR	Spectral Type	b (mag)	$\bar{P}$	$\sigma(P)$	$\bar{\theta}$	E_{B-V}	P_{IS}	$\sigma_{P_{IS}}$	θ_{IS}	$\sigma_{\theta_{IS}}$	Number of Stars	Radius
190918.........	133	WN4.5 + O9.5 Ia	7.6	0.472%	0.024%	160°3	0.56	1.123%	0.157%	148°4	7°7	36	2°
191765.........	134	WN6	8.6	0.954	0.044	4.0	0.61	1.176	0.166	144.4	7.7	43	2
192103.........	135	WC8	8.5	0.225	0.023	7.6	0.32	0.459	0.078	153.2	9.8	38	2
192163.........	136	WN6	8.0	1.450	0.027	177.5	0.61	1.225	0.194	12.5	4.8	41	2
192641.........	137	WC7 + abs	8.3	1.175	0.023	187.5	0.61	0.962	0.156	122.9	46.1	43	2
193077.........	138	WN5 + abs	8.5	0.688	0.030	100.5	0.56	0.866	0.118	54.6	7.1	55	2
193576.........	139	WN5 + O6	8.6	0.402	0.032	147.6	0.82	1.639	0.200	50.0	4.3	63	2
193793.........	140	WC7 + O4 V	7.4	1.367	0.033	32.7	0.69	1.383	0.255	71.4	30.9	34	4

Note.—The catalog of van der Hucht *et al.* 1981 classified HD 193793 as a WC7 + abs system. Now there is good evidence for the absorption lines to be due to an O-type companion. The absorption lines of HD 192641 and HD 193077 have also been proposed, somewhat less conclusively, to arise in an O star companion (see text for details).

MINIPOL polarimeter (Frecker and Serkowski 1965) of the University of Arizona. Only a few data (those from Mont Mégantic) were collected with a Pockels cell polarimeter of the type described by Angel and Landstreet (1970). All the measurements were made through a blue Corning filter 4-96 (centered at 4700 Å with a FWHM bandpass of 1800 Å) using a diaphragm of ~10″ diameter. A precision of $\sigma_P \leq 0.015\%$ was obtained in ~15 minutes for each object in 1985 and 1986, and it was somewhat worse in 1984.

The observations of unpolarized stars revealed negligible instrumental polarization ($P_{\rm inst} \leq 0.010\%$) for each run (except at Mont Mégantic, where $P_{\rm inst} \simeq 0.15\%$; this instrumental polarization was then appropriately subtracted). Many polarized stars were also observed in order to calibrate the origin of the position angle. The small variability discovered for most of the polarized standards (Bastien *et al.* 1988) is largely compensated, for the data collected in 1985 and 1986, by the large number of standards observed. The efficiency of the polarimeters was measured by introducing a polarizing prism ($P = 99.9\%$) into the light beam. The MINIPOL revealed a constant efficiency (of ~98%) from night to night for each run. The efficiency of the Mont Mégantic polarimeter averaged ~90% after adjustment for the temperature dependence. In each case the measured efficiency was used to correct the observed polarization values. The prism measurements were also employed to verify the position angles.

The interstellar medium also contributes to the polarization observed. Figure 1 shows the polarization vectors of stars mea-

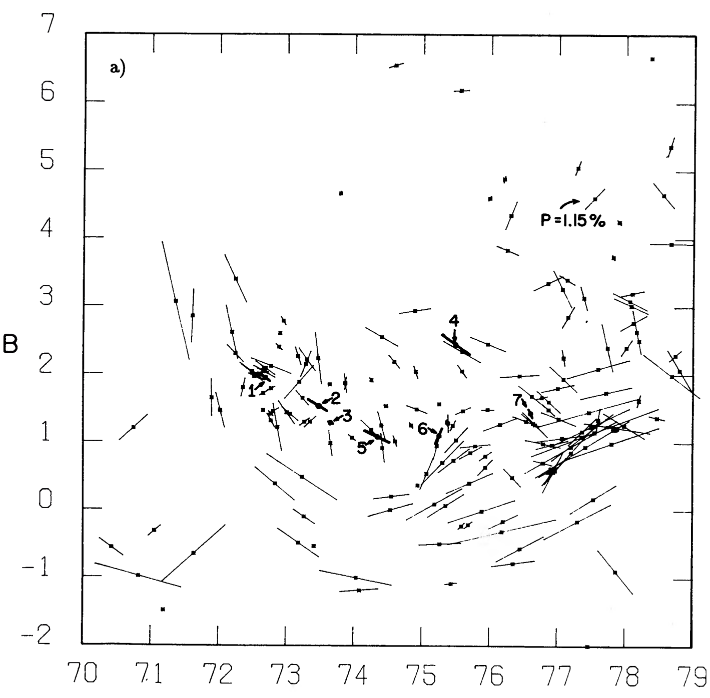

Fig. 1*a*

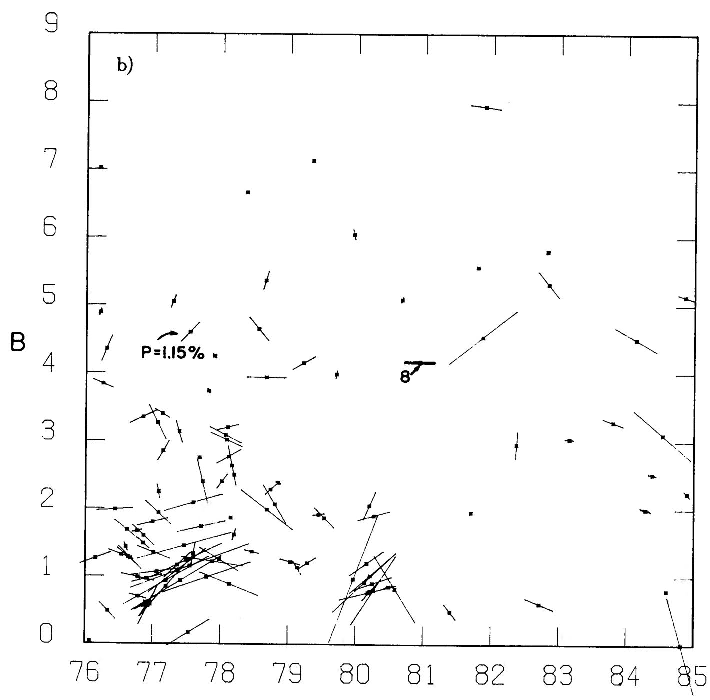

Fig. 1*b*

Fig. 1.—Polarization maps for stars in 9° × 9° regions around and within ±ΔDM of the true distance modulus (DM) of the eight bright Cygnus WR stars. (*a*) With DM = 11.2 mag (the average value for the WR stars involved) and ΔDM = 2.5 mag (to show all the surrounding stars used in the calculation of the interstellar polarization for each WR star), contains (1) HD 190918, (2) HD 191765, (3) HD 192103, (4) HD 192163, (5) HD 192641, (6) HD 193077, and (7) HD 193576. (*b*) Overlaps partly the first map, with DM = 10.8 mag and ΔDM = 4.0 mag, and contains (8) HD 193793. The length of the vectors and their orientation are proportional to *P*(%) and θ in the Galactic coordinate system. The actual value of *P* for a well-isolated star is indicated. Polarization vectors for the eight WR stars are taken from the present mean values.

sured previously in two 9° × 9° regions surrounding the bright Cygnus WR stars. In the calculation of the interstellar component of polarization for each WR star, we have selected stars included in a circle of 2° radius centered on the WR star and having a difference of their distance modulus with that of the WR star no greater than ±2 mag (except for HD 193793, where the circle radius is 4° and differences in modulus were allowed to reach ±4 mag, in order to include a reasonable number of stars). Table 1 contains for each star the (assumed) interstellar polarization, P_{IS} and θ_{IS} (see Appendix B of Bastien 1985 for a description of the method used to calculate these parameters), and their standard deviations, $\sigma_{P_{IS}}$ and $\sigma_{\theta_{IS}}$. Table 1 also contains the average polarization $[\bar{P} = (\bar{Q}^2 + \bar{U}^2)^{1/2}$ and $\bar{\theta} = \frac{1}{2}\arctan(\bar{U}/\bar{Q})]$ observed here for each Cygnus WR star. The parameter of $\sigma(P)$ is the scatter in P defined by

$$\sigma(P)^2 = \frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{\sigma_{P_i}}{P_m}\right)^2[(Q_i - Q_m)^2 + (U_i - U_m)^2]\,, \quad (1)$$

where N is the number of data points collected for a star and σ_{P_i} is the observational error of P_i. Values of Q_m, U_m, and P_m are the means of the Stokes parameters in the case of a single WR star or the phase-dependent result of the best fit in the case of a binary. Comparison of the observed average WR polarization with the interstellar value does not reveal any particular case where the averaged polarization can be unambiguously claimed to be totally of interstellar origin. In some cases the two angles are close; in other cases the degrees of polarization are similar. The discrepancies are probably mainly caused by large fluctuations in the interstellar and possibly intrinsic polarization. From Figure 1, one can see that the polarization vectors of the surrounding stars have a very chaotic pattern.

III. RESULTS AND DISCUSSION OF INDIVIDUAL STARS

First, we present and discuss the polarimetric data obtained for the well-known binary HD 190918. The WR + O system with a long period, HD 193793, is treated in the second part, along with the two possible candidates for a wide orbit, HD 192641 and HD 193077. The suspected WR + c systems, HD 192163 and HD 191765, are then considered, followed by the single star, HD 192103. The short period eclipsing system V444 Cyg will be discussed in detail in Paper VI.

a) The WR + O Binary HD 190918 (WR 133): WN4.5 + O9.5 Ia

The spectrum of HD 190918 is composed of broad, diluted emission lines and narrow absorption lines. Wilson (1949) found a small amplitude of variation in the radial velocity data and then qualified this object as a binary system.

The polarization data collected for HD 190918 are compatible with its binary nature. Figure 2 shows the parameters Q and U from Table 2, plotted against orbital phase, which was calculated with the new spectroscopic period, 112.8 ± 0.5 days, and the time of periastron passage, JD 2,431,967.8 ± 1.6, deduced by Fraquelli, Bolton, and Horn (1987, hereafter FBH). The solid curves of Figure 2 are obtained with the eccentric orbit model of Brown *et al.* (1982) which gives (after correction; see Simmons and Boyle 1984):

$$Q' = \frac{-\tau_*}{(1-e^2)^2}[1 + e\cos(\lambda - \lambda_p)]^2 \times [(1 + \cos^2 i)\cos 2\lambda - \sin^2 i]\,,$$

$$U' = \frac{-2\tau_*}{(1-e^2)^2}\{1 + e\cos(\lambda - \lambda_p)\}^2 \cos i \sin 2\lambda\,, \quad (2)$$

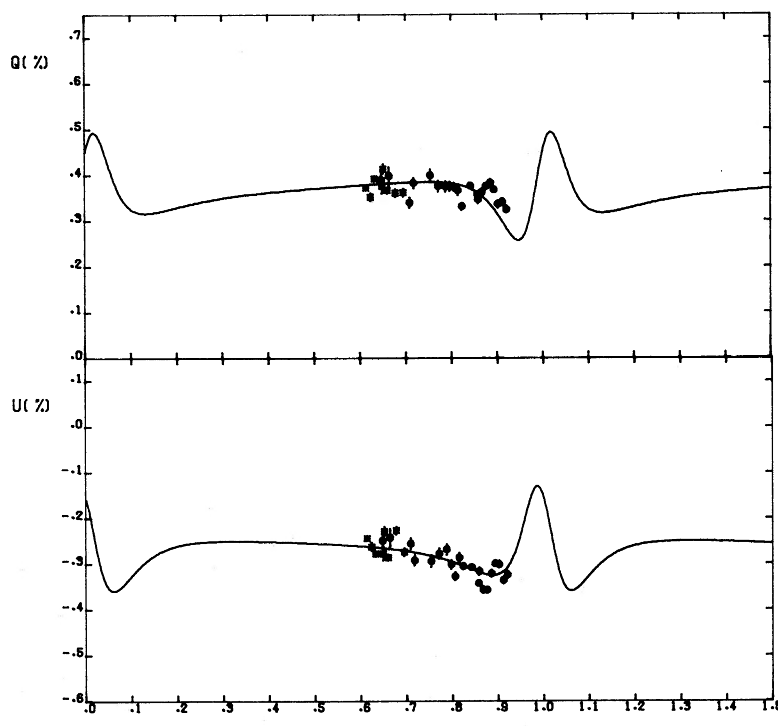

FIG. 2.—Stokes parameters Q and U for HD 190918 plotted against orbital phase, calculated using the FBH ephemeris (112.8 day period and the time of periastron passage JD 2,431,967.8). Solid curves are the best fit to the eccentric model. Measurements from 1985 and 1986 are plotted with asterisks and circles, respectively. Vertical bars, here and in all the figures, are 2 σ error estimates purely due to photon statistics.

and

$$Q = Q_0 + Q' \cos \Omega - U' \sin \Omega ,$$
$$U = U_0 + Q' \sin \Omega + U' \cos \Omega , \quad (3)$$

where λ is the orbital longitude of the scattering region, measured from the plane containing the orbital axis and the Earth. It is calculated in the usual way from the orbital phase, via the eccentric anomaly and Kepler's equation. The parameter τ_* is related to the electron density around the WR star; i and e are the orbital inclination and eccentricity, respectively. The longitude of perihelion, is given by λ_p (deduced from ω_{WR}, the same longitude but given with respect to the line of nodes). The angle between the major axis of the ellipse in the $Q-U$ plane and the Q-axis (taken parallel to the celestial north pole) is symbolized by Ω. The quantities Q_0 and U_0 correspond to the average level of Q and U. The model curves of Figure 2 were calculated with the parameters given by FBH:

$$e = 0.48 \pm 0.04 ,$$
$$\lambda_p = \omega_{WR} - 90° = 306° \pm 8° ,$$
$$i = 165° .$$

FBH calculated an inclination $i \simeq 15°$ assuming a mass of 30 $M_\odot$ for the O9.5 Ia companion. Better agreement of the eccentric model with the polarimetric observations was found with the complimentary angle of i (given by $180° - i = 165°$), which corresponds to retrograde motion. Note that unlike the case of the polarization orbit, the radio velocity orbit cannot distinguish between i and $180° - i$. The best fit was obtained for

$$\Omega = 130° \pm 20° ,$$
$$\tau_* = 0.020 \pm 0.005 ,$$
$$Q_0 = 0.360\% \pm 0.005\% ,$$
$$U_0 = -0.270\% \pm 0.005\% .$$

The errors given for these parameters are very crude estimates based on visual inspection of curves superposed on the data for a grid of different values of Ω, τ_*, Q_0, and U_0.

Other models with different values of i were also fitted to the observations. For these models, τ_* was found to be strongly coupled to i, while the other parameters Ω, Q_0, and U_0 remained almost unaffected. Unfortunately, the observations cover only about one-third of the orbit and avoid the time of periastron passage ($\varphi = 0$). This part of the orbit is crucial in determining i and τ_* because these parameters are directly related to the amplitude of Q and U in a different manner (see eqs. [2] and [3]). Because of the lack of data at the time of periastron passage, we cannot yet estimate precise values of i and τ_*. Nevertheless, Ω seems to be constrained to a value close to 130°.

It is also worth noting the relatively small dispersion in polarization around the eccentric orbit model of HD 190918, compared to the other known WR stars with supergiant companions, γ^2 Vel and θ Mus (Paper I). For all three binaries, the

TABLE 2

LINEAR POLARIZATION DATA FOR HD 190918

Julian Date (2,446,000+)	P	σ_P	θ	σ_θ	Q	U	Phase[a]	Source
362.704.........	0.444%	0.005%	163°.3	0°.3	0.371%	−0.244%	0.614	1
363.751.........	0.438	0.009	161.6	0.6	0.351	−0.262	0.624	1
364.754.........	0.480	0.006	162.3	0.4	0.391	−0.278	0.633	1
366.575.........	0.466	0.016	161.8	1.0	0.375	−0.277	0.649	1
366.786.........	0.472	0.011	165.5	0.7	0.413	−0.229	0.651	1
367.802.........	0.464	0.007	161.0	0.4	0.366	−0.286	0.660	1
369.722.........	0.425	0.009	163.9	0.6	0.360	−0.226	0.677	1
371.765.........	0.453	0.009	161.4	0.6	0.361	−0.274	0.695	1
704.787.........	0.462	0.016	163.7	1.0	0.389	−0.249	0.647	2
706.683.........	0.465	0.020	164.3	1.2	0.397	−0.242	0.664	2
711.822.........	0.424	0.012	161.5	0.8	0.339	−0.255	0.709	2
712.631.........	0.481	0.012	161.3	0.7	0.382	−0.292	0.717	2
716.827.........	0.496	0.014	161.8	0.8	0.399	−0.294	0.754	2
718.755.........	0.466	0.012	161.8	0.7	0.375	−0.277	0.771	2
720.719.........	0.460	0.012	162.2	0.7	0.374	−0.268	0.788	2
721.729.........	0.481	0.010	160.6	0.6	0.375	−0.301	0.797	2
722.710.........	0.497	0.009	159.4	0.5	0.374	−0.327	0.806	2
723.741.........	0.464	0.011	161.0	0.7	0.366	−0.286	0.815	2
724.729.........	0.450	0.008	158.7	0.5	0.331	−0.305	0.824	2
726.737.........	0.485	0.006	160.4	0.4	0.376	−0.307	0.842	2
728.613.........	0.495	0.004	158.1	0.2	0.357	−0.343	0.858	2
728.724.........	0.469	0.009	158.8	0.5	0.346	−0.316	0.859	2
729.697.........	0.509	0.008	157.7	0.5	0.362	−0.357	0.868	2
730.638.........	0.518	0.007	158.2	0.4	0.375	−0.357	0.876	2
731.704.........	0.500	0.008	160.0	0.5	0.383	−0.321	0.886	2
732.641.........	0.473	0.006	160.4	0.4	0.367	−0.299	0.894	2
733.666.........	0.451	0.008	159.1	0.5	0.336	−0.301	0.903	2
734.642.........	0.479	0.008	157.7	0.5	0.341	−0.336	0.912	2
735.690.........	0.458	0.008	157.5	0.5	0.324	−0.324	0.921	2

[a] The orbital phase is calculated using the 112.8 day period and the time of perias ron passage JD 2,431,967.8 from FBH.

SOURCES.—(1) 1985, Mount Lemmon and Mount Bigelow. (2) 1986, Mount Lemmon.

light of the O supergiant dominates, but for γ^2 Vel and θ Mus the scatter in polarization is relatively high, possibly because of nonradial pulsations (NRP) of the supergiant. One must then conclude that the O star companion in HD 190918 is a relatively stable supergiant.

b) WR + abs Objects

The presence of absorption lines, similar to those seen in O stars, in the spectra of the three Cygnus WR stars HD 192641, HD 193077, and HD 193793, originally led astronomers to qualify these stars as binary systems. This later became questionable because of the lack of detectable binary orbital motion.

The possibility of a chance line-of-sight O star, proposed by Conti *et al.* (1984) for HD 193793, was virtually eliminated by Moffat *et al.* (1986). Their speckle interferometry for these three stars failed to reveal any companion of $|\Delta m| < 2$ mag down to a separation of 0.″05.

i) *HD 193793 (WR 140): WC7 + O4 V*

The existence of an orbiting O companion in HD 193793 has finally been established unequivocally after a long compilation of the IR emission and radial velocity data.

Hackwell *et al.* (1976) observed a reduction of the IR emission between 1970 and 1975. This behavior was interpreted as a drop of $\dot{M}$ for a free-free emission model. An IR burst then occurred at the beginning of 1977 (Hackwell, Gehrz, and Grasdalen 1979). This burst, as well as one observed in 1985 (Williams, van der Hucht, and Thé 1987), was claimed to be related to the triggering of dust condensations around the star (see also Williams *et al.* 1978). It is known that late-type, low-ionization WR stars (WC9 and some WC8) tend to be surrounded by dust shells. However, the IR flux from these stars does not generally vary, implying a constant rate of dust formation.

Finally, when Williams *et al.* (1987) combined all existing IR data and radial velocity measurements for HD 193793, a long periodicity of 7.9 yr emerged. The analysis of radial velocity data, including new observations, repeated by Moffat *et al.* (1987), confirmed the long period (7.9 ± 0.2 yr, with the time of periastron passage JD $2{,}423{,}069 \pm 35$) and an eccentricity of 0.7. The resulting masses of each component are compatible with the masses found for stars of similar spectral type in other systems. Williams *et al.* (1987) proposed that the IR bursts (observed just before the periastron passage) are triggered by the collision of the two stellar winds, which is greatly intensified at periastron.

The radio spectrum of HD 193793 has shown both free-free emission (Becker and White 1985) and nonthermal emission at a time coinciding with the IR bursts (Florkowski and Gottesman 1977; Florkowski 1982; Abbott and Conti 1987). HD 193793 is the intrinsically brightest X-ray source known among WR stars (Pollock 1987). The X-ray fluxes measured in 1977 and 1984 (after an IR burst) were nevertheless associated with the normal stellar wind.

The present polarimetric observations of HD 193793 are presented in Figure 3 and Table 3. A search for periodicity

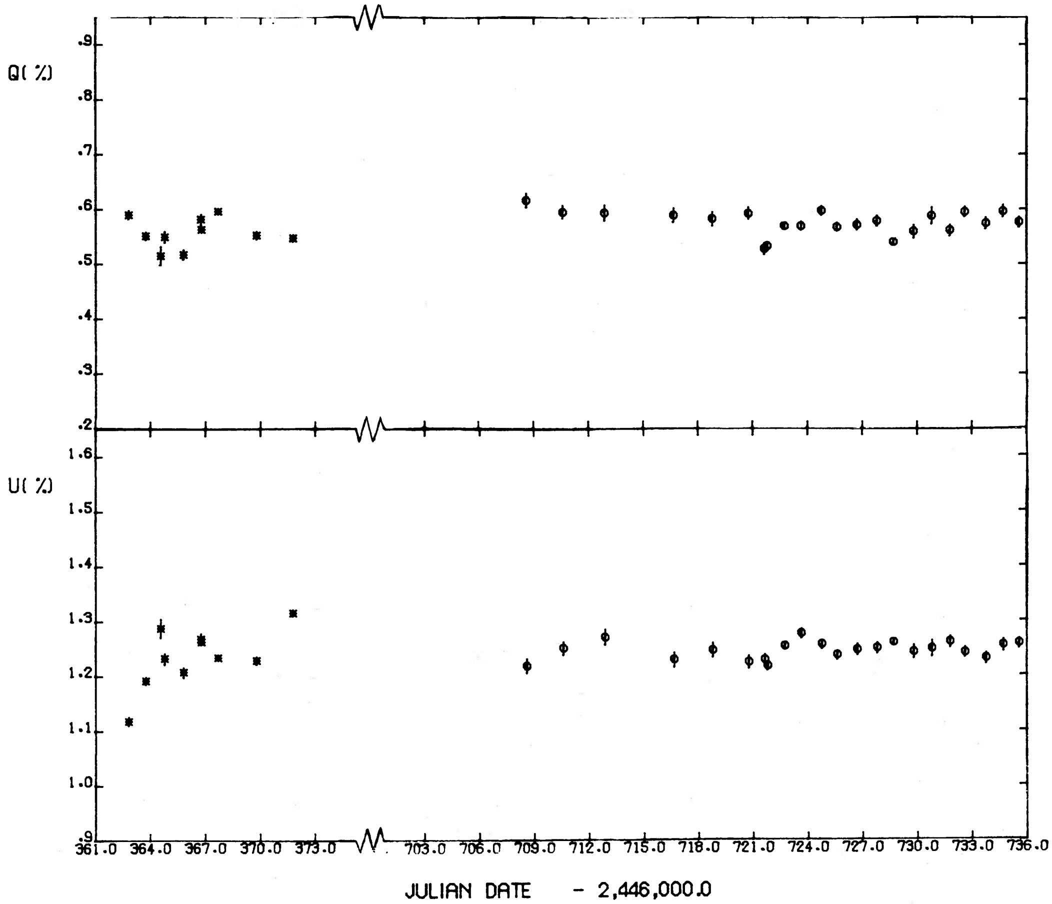

FIG. 3.—Stokes parameters Q and U plotted as a function of Julian Date for HD 193793. Symbols are as in Fig. 2.

TABLE 3

LINEAR POLARIZATION DATA FOR HD 193793

Julian Date (2,446,000+)	P	σ_P	θ	σ_θ	Q	U	Source[a]
362.798	1.264%	0.008%	31°.1	0°.2	0.590%	1.118%	1
363.741	1.313	0.007	32.6	0.2	0.551	1.192	1
364.560	1.387	0.017	34.1	0.4	0.515	1.288	1
364.780	1.349	0.010	33.0	0.2	0.549	1.232	1
365.814	1.313	0.009	33.4	0.2	0.517	1.207	1
366.743	1.395	0.010	32.7	0.2	0.581	1.268	1
366.767	1.383	0.005	33.0	0.1	0.563	1.263	1
367.692	1.369	0.004	32.1	0.1	0.596	1.233	1
369.787	1.346	0.007	32.9	0.1	0.552	1.228	1
371.774	1.424	0.006	33.7	0.1	0.547	1.315	1
708.603	1.366	0.013	31.6	0.3	0.616	1.219	2
710.593	1.385	0.012	32.3	0.2	0.594	1.251	2
712.882	1.402	0.014	32.5	0.3	0.593	1.271	2
716.647	1.364	0.013	32.2	0.3	0.589	1.230	2
718.784	1.376	0.013	32.5	0.3	0.582	1.247	2
720.738	1.361	0.011	32.1	0.2	0.592	1.225	2
721.615	1.337	0.010	33.4	0.2	0.527	1.229	2
721.771	1.329	0.008	33.2	0.2	0.532	1.218	2
722.734	1.377	0.006	32.8	0.1	0.569	1.254	2
723.625	1.398	0.008	33.0	0.2	0.569	1.277	2
724.739	1.392	0.008	32.3	0.2	0.597	1.257	2
725.596	1.361	0.008	32.7	0.2	0.567	1.237	2
726.679	1.371	0.010	32.7	0.2	0.571	1.247	2
727.782	1.377	0.009	32.6	0.2	0.578	1.250	2
728.684	1.371	0.005	33.4	0.1	0.540	1.260	2
729.781	1.363	0.012	32.9	0.3	0.559	1.243	2
730.775	1.380	0.015	32.4	0.3	0.588	1.249	2
731.789	1.380	0.010	33.0	0.2	0.561	1.261	2
732.585	1.377	0.009	32.2	0.2	0.595	1.242	2
733.751	1.358	0.010	32.5	0.2	0.574	1.231	2
734.699	1.389	0.011	32.3	0.2	0.596	1.255	2
735.575	1.384	0.009	32.7	0.2	0.576	1.258	2

[a] Sources as in Table 2.

(using two different programs: one based on the nonparametric method of Lafler and Kinman 1965, and the other by Lamontagne 1983 based on fitting sine waves) fails to reveal any significant periods.

The period of 7.9 yr cannot be verified yet on the basis of these data because of inadequate phase coverage. Nevertheless, one small clue in favor of this long orbit is that the observations of 1985, which are closer to the time of periastron passage, show marginally more scatter than in 1986. (The orbital inclination might also play an important role in this behavior, explaining why the scatter is greater in U than in Q.)

Table 4 contains average values of linear polarization from different observers. Orbital phases, given in the last column of Table 4, are different for each group of data. Little can be said about the binary modulation in polarization because of the different domains of wavelength observed.

The polarization from electron scattering is not expected to be a function of the wavelength of the incident photon, but the

TABLE 4

AVERAGE LINEAR POLARIZATION VALUES FOR HD 193793

Reference	Mean JD	Filter	$\bar{P}$[a]	$\bar{\theta}$[b]	n	Phase[c]
Hall 1958	≃2,433,284	No	1.2%	35°	2	≃0.5
Coyne 1974	2,440,416	B[d]	1.47	34.4	2	0.012
1985, Mount Lemmon and Mount Bigelow	2,446,366	B	1.354 (0.052)	32.9	10	0.074
1986, Mount Lemmon	2,446,725	B	1.373 (0.017)	32.6	22	0.198

[a] $\bar{P} = (\bar{Q}^2 + \bar{U}^2)^{1/2}$. The error for $\bar{P}$ indicated in parentheses is the standard deviation deduced from the n observations.

[b] $\bar{\theta} = \frac{1}{2} \arctan (\bar{U}/\bar{Q})$.

[c] The orbital phase is calculated with the 7.9 yr period and the time of periastron passage JD 2,423,069 from Moffat *et al.* 1987.

[d] The B filter used by Coyne 1974 is centered at ≃4300 Å with $\Delta\lambda \simeq 1000$ Å (different from our B filter centered at 4700 Å with $\Delta\lambda = 1800$ Å).

interstellar contribution to the observed polarization is, on the other hand, wavelength dependent. Caution should be exercised, however, since dust formation and dissipation are thought to occur in the system. Dust could produce a significantly variable component of polarization, also wavelength dependent, which would add to the orbital component from electron scattering.

ii) *HD 192641 (WR 137): WC7 + abs*

As in the case of HD 193793, the IR emission of HD 192641 has shown unusually strong variations. Between 1970 and 1975, the IR flux slowly decreased (Hackwell *et al.* 1976; Williams *et al.* 1985) and then became brighter after 1978. These variations were claimed to arise in changes of $\dot{M}$, the electron density, or the radius of the envelope, or as a consequence of condensation and dissipation of dust shells. With an interval of ~12 yr between two successive IR bursts (Williams, van der Hucht, and Thé 1987) this star might be a long period binary in an elliptical orbit, much like HD 193793.

The analysis of radial velocity data by Massey, Conti, and Niemela (1981) and by Moffat *et al.* (1986) showed no clear sign of duplicity. Neither have any significant photometric variations been detected so far (Cherepashchuk 1975*a*; Moffat and Shara 1986).

Among the Cygnus WR stars, HD 192641 also shows the smallest level of polarimetric variations (Fig. 4 and Table 5). No periodicity is found after a search through each group of the present polarimetric data (1985 or 1986), or through all these data together. Table 6 contains the average Stokes parameters for each group of new data and for other previous observations (Hiltner 1951; Coyne 1974). The higher average obtained by Coyne at JD 2,440,416 (1969) compared to the observation 1 yr later (JD 2,440,854) in the same filter could be correlated to the IR decrease of 1970–1975. We suppose that a burst occurred around 1968, leading to an increase of the degree of polarization. The last column of Table 6 shows the orbital phases for a 12 yr period using an emphemeris of phase zero in 1968. The constancy of the new data is consistent with this period, since the new observations fall at the long lasting time of large separation for a wide eccentric binary. The unknown wavelength dependence of the polarization or the presence of dust could also confuse possible variations between the different epochs of data. The polarization data of HD 192641 can also be simply interpreted as if arising in a single star.

iii) *HD 193077 (WR 138): WN5 + abs*

The IR emission of HD 193077 observed by Hackwell, Gehrz, and Smith (1974) was easily explained by a free-free emission model. The IR and X-ray flux behavior (Pollock 1987) appears normal so far.

Massey (1980) claimed to have discovered hydrogen in the emission-producing envelope. This could imply that there is still hydrogen in the WR photosphere, which may be responsible for the absorption lines dominated by the Balmer series. Intrinsic absorption lines are usually found only in

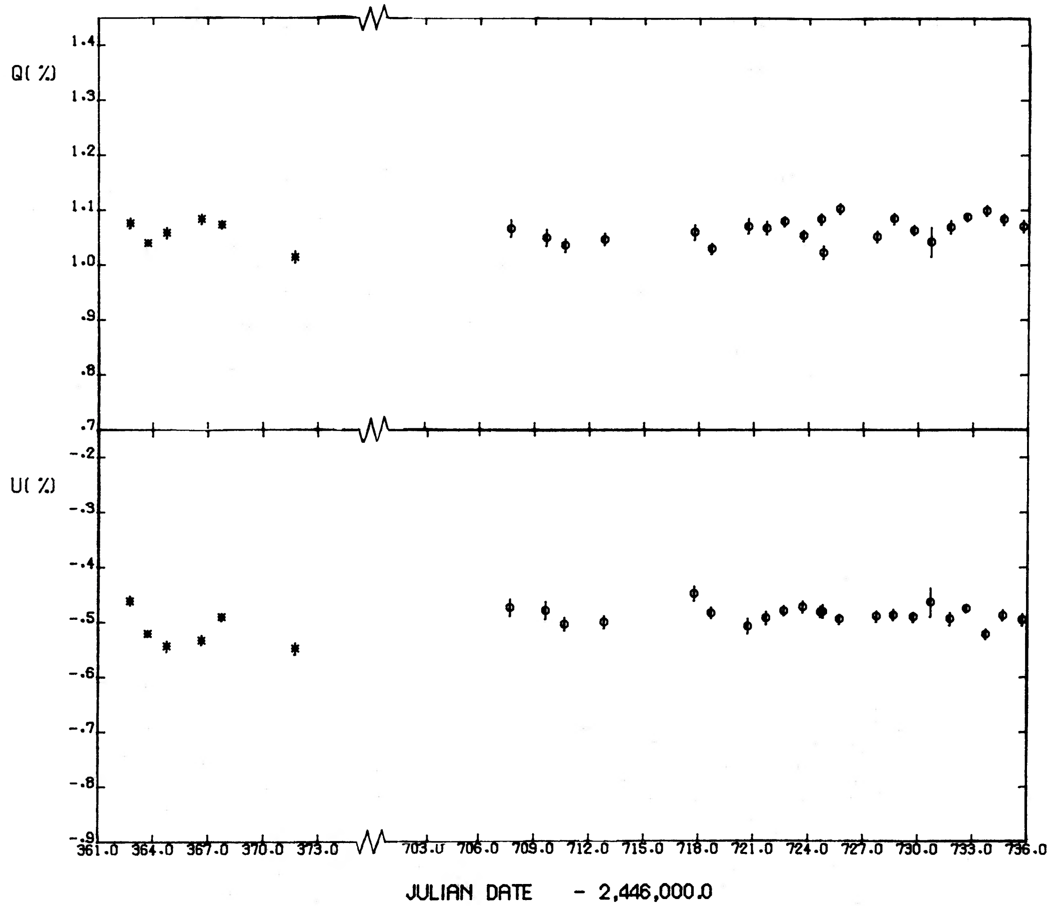

FIG. 4.—Stokes parameters Q and U plotted as a function of Julian Date for HD 192641. Symbols are as in Fig. 2.

TABLE 5

LINEAR POLARIZATION DATA FOR HD 192641

Julian Date (2,446,000+)	P	σ_P	θ	σ_θ	Q	U	Source[a]
362.762	1.171%	0.009%	168°4	0°2	1.076%	−0.461%	1
363.725	1.163	0.005	166.7	0.1	1.040	−0.521	1
364.737	1.190	0.010	166.4	0.2	1.058	−0.544	1
366.667	1.207	0.009	166.9	0.2	1.083	−0.533	1
367.764	1.180	0.007	167.7	0.2	1.073	−0.491	1
371.755	1.153	0.011	165.8	0.3	1.014	−0.548	1
707.685	1.167	0.016	168.0	0.4	1.066	−0.475	2
709.611	1.154	0.016	167.7	0.4	1.049	−0.480	2
710.661	1.152	0.012	167.0	0.3	1.035	−0.505	2
712.828	1.160	0.011	167.2	0.3	1.046	−0.501	2
717.736	1.150	0.014	168.5	0.3	1.059	−0.449	2
718.702	1.137	0.010	167.4	0.3	1.029	−0.484	2
720.672	1.184	0.014	167.3	0.3	1.070	−0.508	2
721.675	1.175	0.012	167.6	0.3	1.067	−0.493	2
722.666	1.181	0.009	168.0	0.2	1.079	−0.480	2
723.693	1.154	0.010	167.9	0.2	1.053	−0.473	2
724.655	1.186	0.010	168.0	0.2	1.083	−0.482	2
724.787	1.130	0.012	167.4	0.3	1.022	−0.481	2
725.703	1.208	0.009	167.9	0.2	1.102	−0.495	2
727.729	1.160	0.010	167.5	0.2	1.051	−0.490	2
728.651	1.188	0.010	167.9	0.2	1.084	−0.487	2
729.744	1.171	0.009	167.6	0.2	1.063	−0.491	2
730.699	1.141	0.027	168.0	0.7	1.042	−0.464	2
731.735	1.178	0.012	167.6	0.3	1.069	−0.494	2
732.668	1.186	0.007	168.2	0.2	1.087	−0.475	2
733.708	1.217	0.009	167.3	0.2	1.099	−0.522	2
734.670	1.187	0.010	167.9	0.2	1.083	−0.487	2
735.716	1.179	0.011	167.6	0.3	1.070	−0.495	2

[a] Sources as in Table 2.

massive WNL stars for which the WR type mass-loss process is just starting (the winds are less dense than in more evolved WNE or WC stars). Nevertheless, combined with the fact that he claimed not to have found any significant variations of the radial velocity (covering a range of 15 yr) and that the absorption lines are broader than those seen in most O stars, Massey (1980) concluded that HD 193077 is a single, rapidly rotating WR star with a low-density H-rich wind. A more recent radial velocity analysis by Lamontagne (1983), which included the previous observations of Bracher (1966), Massey (1980), and Lamontagne *et al.* (1982), revealed a possible orbit with a period of 1749 days (or 1533 days as a close second possibility) and reasonable values for the masses. A revised spectral type of WN6 + O was also given. More recently Annuk (1989) has confirmed and refined the orbit of Lamontagne (1983) with a period of 1538 days.

The small temporal variations of the polarization for HD 193077 are presented in Figure 5 and Table 7. No significant periodicity was found in these data. Because of an insufficient time span, the suggested long period of 1538 days cannot be verified yet. The averaged Stokes parameters measured around 1950 for nonfiltered light (Hiltner 1951) are very similar to the recent observations (Table 8). With a periodicity of 1538 days, there are ~8.6 orbital cycles between each epoch

TABLE 6

AVERAGE LINEAR POLARIZATION VALUES FOR HD 192641

Reference	Mean JD	Filter	$\bar{P}$[a]	$\bar{\theta}$[b]	n	Phase[c]
Hiltner 1951	≃2,433,284	No	1.2%	168°	?	≃0.5
Coyne 1974	2,440,416	B[d]	1.36	169.1	2	0.128
Coyne 1974	2,440,854	B[d]	1.19	168.3	2	0.228
1985, Mount Lemmon and Mount Bigelow	2,446,366	B	1.174 (0.027)	167.0	6	0.485
1986, Mount Lemmon	2,446,724	B	1.175 (0.021)	167.5	22	0.567

[a] Same as in Table 4.
[b] Same as in Table 4.
[c] The orbital phase is calculated with the approximate 12 yr period, from Williams, van der Hucht, and Thé 1987, and the ephemeris for the time of periastron passage around 1968: JD 2,439,856 (based on the IR data).
[d] Same as in Table 4.

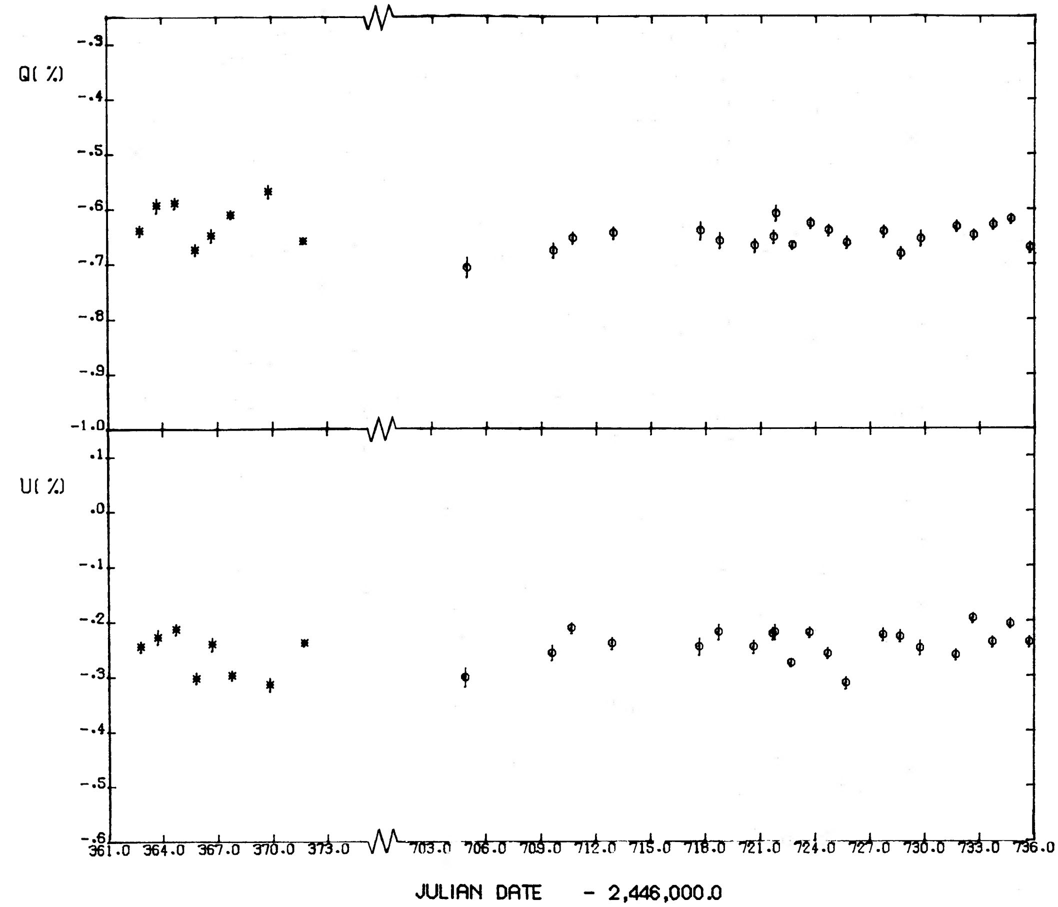

FIG. 5.—Stokes parameters Q and U plotted as a function of Julian Date for HD 193077. Symbols are as in Fig. 2.

of data. The few polarimetric observations resemble those found for a single star, but this does not eliminate the possibility of a long orbit.

c) *WR + c Candidates*

Two of the bright Cygnus WR stars have been suspected to be WR + c binaries. These are the two WN6 stars HD 191765 and HD 192163. In either case, the low-mass companion is claimed to be a neutron star (according to the interpretation of the photometric variability of HD 191765 by Antokhin, Aslanov, and Cherepashchuk 1982 and the radial velocity variability of HD 192163 by Aslanov and Cherepashchuk 1981).

These two objects share another point: they are surrounded by ring-shaped nebulosity. NGC 6888, associated with HD 192163, is the nearest, brightest and most regular nebulosity known around any WR star. The thin, ellipsoidal shell, nearly centered on HD 192163, shows a prominent filamentary structure (Wendker *et al.* 1975). The nebulosity associated with HD 191765 forms a more discrete filamentary bubble (Heckathorn, Bruhweiler, and Gull 1982; Treffers and Chu 1982). Several hypotheses have been proposed to explain the formation of the nebulosity. One of them simply invokes the interaction of the stellar wind with the ambient interstellar medium (Johnson and Hogg 1965) and should be visible around any WR star in principle. Other investigators have associated the nebulosity with the presence of a compact companion; the nebulosity is supposed to have been formed by mass transfer from the WR progenitor into the compact companion at such a rapid rate that the companion became bloated and much of the matter was ejected on a short time scale (Lozinskaya 1980).

i) *HD 192163 (WR 136): WN6*

The normalized Stokes parameters Q and U observed from 1984 to 1986 in the same broad-band blue filter are presented in Figure 6 and Table 9. Figure 6 shows short time scale variations in Q and U of relatively low amplitude. The mean value of the polarization data published by Hall (1958) (see Table 10) deviates considerably from later observations. The discrepancy may be due to the difference in effective wavelength. The possibility of a sudden or slow change of $\dot{M}$ or even the existence of an unknown companion in a wide elliptical orbit cannot be excluded here.

The polarimetric variability of HD 192163 does not reveal any of the periodicities claimed in the past on the basis of spectroscopic and photometric data. The 4.554 day period, found originally in the line profile variations of Koenigsberger, Firmani, and Bisiacchi (1980), in the radial velocity data of Aslanov and Cherepashchuk (1981), and in the photometry of Antokhin and Cherepashchuk (1985), is not present here in the polarization data. This periodicity was also absent in the radial velocity data of Lamontagne (1983) and in the broad-band photometry of Moffat and Shara (1986). Vreux, Andrillat, and Gosset (1985) have argued, from a second analysis of the previous radial velocity data supplemented by new measurements, that this period was less favourable than the alias periods of

TABLE 7

LINEAR POLARIZATION DATA FOR HD 193077

Julian Date (2,446,000+)	P	σ_P	θ	σ_θ	Q	U	Source[a]
362.776.........	0.684%	0.010%	100°5	0°4	−0.639%	−0.245%	1
363.732.........	0.635	0.013	100.5	0.6	−0.593	−0.228	1
364.707.........	0.627	0.010	100.0	0.5	−0.589	−0.214	1
365.800.........	0.739	0.010	102.1	0.4	−0.674	−0.303	1
366.676.........	0.691	0.012	100.2	0.5	−0.648	−0.241	1
367.757.........	0.679	0.008	103.0	0.3	−0.610	−0.298	1
369.799.........	0.649	0.012	104.5	0.5	−0.568	−0.315	1
371.730.........	0.700	0.006	100.0	0.2	−0.658	−0.239	1
704.866.........	0.768	0.018	101.6	0.7	−0.706	−0.303	2
709.591.........	0.723	0.014	100.5	0.6	−0.675	−0.259	2
710.643.........	0.686	0.010	99.1	0.4	−0.652	−0.214	2
712.862.........	0.687	0.011	100.3	0.5	−0.643	−0.242	2
717.649.........	0.685	0.016	100.6	0.7	−0.639	−0.248	2
718.727.........	0.693	0.014	99.3	0.6	−0.657	−0.221	2
720.639.........	0.711	0.012	100.2	0.5	−0.666	−0.248	2
721.655.........	0.687	0.011	99.5	0.5	−0.650	−0.224	2
721.786.........	0.646	0.014	100.0	0.6	−0.607	−0.221	2
722.683.........	0.720	0.007	101.3	0.3	−0.665	−0.277	2
723.672.........	0.663	0.009	99.8	0.4	−0.625	−0.222	2
724.680.........	0.689	0.010	101.1	0.4	−0.638	−0.260	2
725.684.........	0.731	0.011	102.7	0.4	−0.660	−0.314	2
727.707.........	0.679	0.011	99.7	0.5	−0.640	−0.226	2
728.668.........	0.718	0.011	99.3	0.4	−0.680	−0.229	2
729.763.........	0.699	0.014	100.5	0.6	−0.653	−0.250	2
731.717.........	0.684	0.010	101.3	0.4	−0.631	−0.263	2
732.653.........	0.676	0.009	98.4	0.4	−0.647	−0.195	2
733.733.........	0.672	0.010	100.4	0.4	−0.628	−0.239	2
734.686.........	0.651	0.009	99.2	0.4	−0.618	−0.205	2
735.733.........	0.711	0.010	99.8	0.4	−0.670	−0.239	2

[a] Sources as in Table 2.

0.45 or 0.31 day. Therefore, they suggested that the variations could be due to NRP. However, either of these two short periods fails to reproduce any type of continuous wave through the polarimetric data.

A systematic search for periodicity reveals interesting behavior. The most significant period found in the 1986 data alone is 7.157 days, with an average χ^2 for Q and U of 0.5. The alias periods, 2.778 and 1.558 days (corresponding to the frequency $\pm\frac{1}{2}$ of the 7.157 day period), also show up at the same level. With the 1984 and 1986 data combined together, the most significant period is 7.080 days, with $\chi^2 \simeq 0.5$ (we have omitted the data of 1984 collected at Mont Mégantic because, at that time, the efficiency of the polarimeter was calibrated using only a few polarized standards, which are now known to be variable to a degree comparable to the precision desired here). This period was tested for reliability according to a program based on the method of Nemec and Nemec (1985), which consists in repeating the periodicity search many times in sets of data formed by randomly mixing the observations in time. A few permutations around the 7.080 day period yielded a similar value of $\chi^2 \simeq 0.5$. This makes the possibility of a real periodicity rather questionable. Finally, the 7.080 day period almost disappeared when the search was carried through all the observations: 1984 (without the Mont Mégantic data), 1985, and 1986.

TABLE 8

AVERAGE LINEAR POLARIZATION VALUES FOR HD 193077

Reference	Mean JD	Filter	$\bar{P}$[a]	$\bar{\theta}$[b]	n
Hiltner 1951	≃2,433,284	No	0.7%	103°	?
1985, Mount Lemmon ..... and Mount Bigelow	2,446,367	B	0.682 (0.039)	101.2	8
1986, Mount Lemmon	2,446,723	B	0.688 (0.025)	100.5	21

[a] Same as in Table 4.
[b] Same as in Table 4.

ii) *HD 191765 (WR 134): WN6*

Figure 7 shows a plot versus time of the parameters Q and U (from Table 11) observed for HD 191765. Among the eight bright Cygnus WR stars, excluding binary modulation in the WR + O systems, HD 191765 shows the largest polarimetric dispersion.

Plots of Q and U versus phase, calculated with the period deduced in other studies, failed to reproduce simultaneous double-wave curves in Q and U. The periods tested were (*a*) the 7.483 day period from the photometry of Antokhin, Aslanov, and Cherepashchuk (1982) and Antokhin and Cherepashchuk (1984) and (*b*) the 1.7844 day period from the radial velocity data of Lamontagne (1983) and (with a similar value of 1.81 days) from the broad-band photometry of Moffat and Shara (1986). The photometry of Antokhin and Volkov (1987) clearly indicates irregular variations over a time scale of months. This effect was explained by a WR + c binary with a precessing neutron star.

An independent search for periodicity among all the polarimetric observations combined together revealed a best period of 1.2707 days, with an average χ^2 for Q and U of 0.66. There are many random permutations of the data that yield a similar value of χ^2 for Q and U.

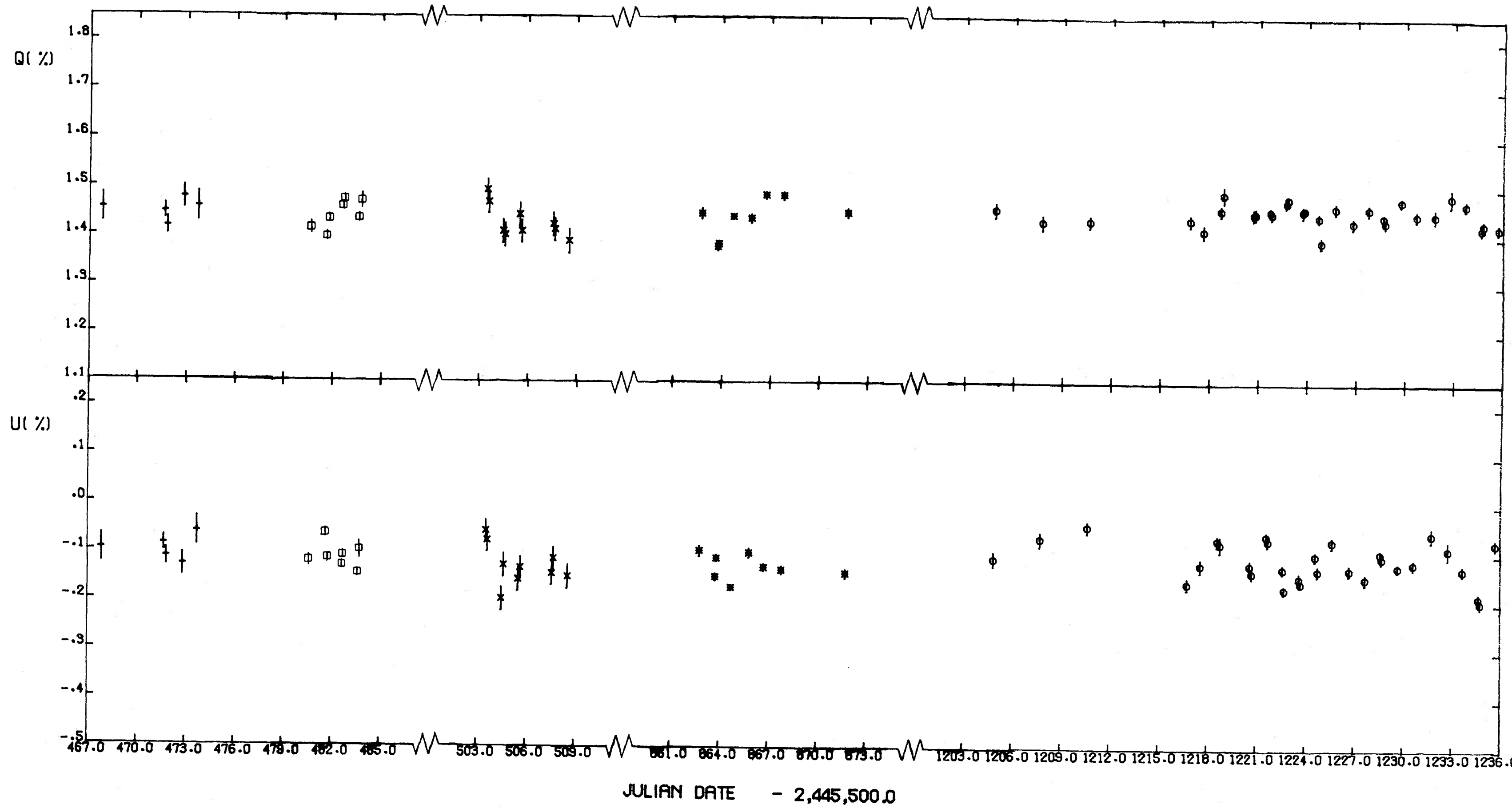

FIG. 6.—Stokes parameters Q and U plotted as a function of Julian Date for HD 192163. Plus signs, squares, and crosses refer to the measurements of 1984 on Mount Bigelow, Mount Lemmon, and Mont Mégantic, respectively. Asterisks and circles represent the recent data of 1985 and 1986.

TABLE 9

LINEAR POLARIZATION DATA FOR HD 192163

Julian Date (2,440,000+)	P	σ_P	θ	σ_θ	Q	U	Source[a]
5967.825	1.457%	0.029%	178°.1	0°.6	1.454%	−0.097%	1
5971.663	1.450	0.015	178.3	0.3	1.447	−0.086	1
5971.825	1.422	0.017	177.7	0.3	1.417	−0.114	1
5972.802	1.483	0.023	177.5	0.4	1.477	−0.129	1
5973.677	1.458	0.030	178.8	0.6	1.457	−0.161	1
5980.671	1.421	0.011	177.6	0.2	1.416	−0.119	2
5981.668	1.399	0.008	178.7	0.2	1.398	−0.063	2
5981.797	1.439	0.007	177.7	0.1	1.434	−0.115	2
5982.650	1.464	0.006	177.5	0.1	1.458	−0.128	2
5982.753	1.478	0.006	177.9	0.1	1.474	−0.108	2
5983.638	1.442	0.007	177.1	0.1	1.435	−0.146	2
5983.786	1.474	0.017	178.1	0.3	1.471	−0.098	2
6003.501	1.495	0.022	178.9	0.4	1.494	−0.057	3
6003.601	1.471	0.023	178.5	0.4	1.469	−0.077	3
6004.478	1.422	0.024	176.0	0.5	1.408	−0.198	3
6004.606	1.407	0.024	177.4	0.5	1.401	−0.128	3
6005.499	1.451	0.024	176.9	0.5	1.443	−0.157	3
6005.632	1.414	0.023	177.3	0.5	1.408	−0.133	3
6007.567	1.430	0.024	177.1	0.5	1.423	−0.145	3
6007.659	1.417	0.023	177.7	0.5	1.412	−0.114	3
6008.533	1.397	0.025	176.9	0.5	1.389	−0.151	3
6362.745	1.449	0.011	178.1	0.2	1.446	−0.096	4
6363.717	1.385	0.007	176.9	0.1	1.377	−0.150	4
6363.784	1.387	0.007	177.7	0.1	1.383	−0.111	4
6364.697	1.450	0.005	176.6	0.1	1.440	−0.172	4
6365.767	1.440	0.009	178.0	0.2	1.436	−0.100	4
6366.684	1.490	0.007	177.5	0.1	1.484	−0.130	4
6367.771	1.489	0.008	177.4	0.2	1.483	−0.135	4
6371.718	1.455	0.009	177.2	0.2	1.448	−0.142	4
6704.842	1.458	0.015	177.8	0.3	1.454	−0.112	5
6707.713	1.431	0.015	178.6	0.3	1.429	−0.070	5
6710.631	1.432	0.012	179.1	0.2	1.431	−0.045	5
6716.783	1.443	0.012	176.8	0.2	1.434	−0.161	5
6717.586	1.417	0.014	177.5	0.3	1.412	−0.123	5
6718.669	1.458	0.011	178.6	0.2	1.456	−0.071	5
6718.809	1.491	0.017	178.5	0.3	1.489	−0.078	5
6720.627	1.453	0.012	177.6	0.2	1.448	−0.122	5
6720.750	1.456	0.011	177.3	0.2	1.450	−0.137	5
6721.641	1.456	0.009	178.8	0.2	1.455	−0.061	5
6721.745	1.452	0.010	178.6	0.2	1.450	−0.071	5
6722.649	1.479	0.009	177.5	0.2	1.473	−0.129	5
6722.765	1.491	0.008	176.7	0.2	1.481	−0.171	5
6723.658	1.462	0.012	177.1	0.2	1.455	−0.148	5
6723.752	1.467	0.007	176.9	0.1	1.458	−0.158	5
6724.640	1.447	0.009	178.0	0.2	1.443	−0.101	5
6724.769	1.398	0.011	177.3	0.2	1.392	−0.132	5
6725.659	1.465	0.011	178.6	0.2	1.463	−0.072	5
6726.714	1.438	0.011	177.4	0.2	1.432	−0.130	5
6727.690	1.468	0.011	177.1	0.2	1.460	−0.148	5
6728.600	1.447	0.008	178.1	0.2	1.444	−0.096	5
6728.695	1.437	0.010	177.9	0.2	1.433	−0.105	5
6729.686	1.482	0.008	177.6	0.2	1.477	−0.124	5
6730.627	1.453	0.010	177.7	0.2	1.448	−0.117	5
6731.764	1.449	0.014	178.9	0.3	1.448	−0.056	5
6732.749	1.488	0.018	178.3	0.3	1.485	−0.088	5
6733.654	1.476	0.010	177.5	0.2	1.470	−0.129	5
6734.617	1.433	0.010	176.3	0.2	1.421	−0.185	5
6734.724	1.443	0.010	176.1	0.2	1.430	−0.196	5
6735.661	1.424	0.010	178.5	0.2	1.422	−0.075	5

[a] SOURCES.—(1) 1984, Mount Bigelow. (2) 1984, Mount Lemmon. (3) 1984, Mont Mégantic. (4) 1985, Mount Lemmon and Mount Bigelow. (5) 1986, Mount Lemmon.

Based on the polarization alone, the WR + c duplicity of HD 191765 and HD 192163 is unlikely; there is no evidence of a clear, unique periodicity. The observed stochastic variations can more easily be explained, for example, by asymmetric ejection of blobs of wind material (see § IV) or by one or many unstable spots formed in magnetic loops extending into the wind. The recent, time-resolved, high-resolution, high signal-to-noise spectroscopy of these stars by Moffat *et al.* (1988) favors random blob ejection.

An important question concerns whether the polarimetric variations refer to asymmetries in a preferred plane or not (e.g., whether the asymmetries occur in a disk or a spherical

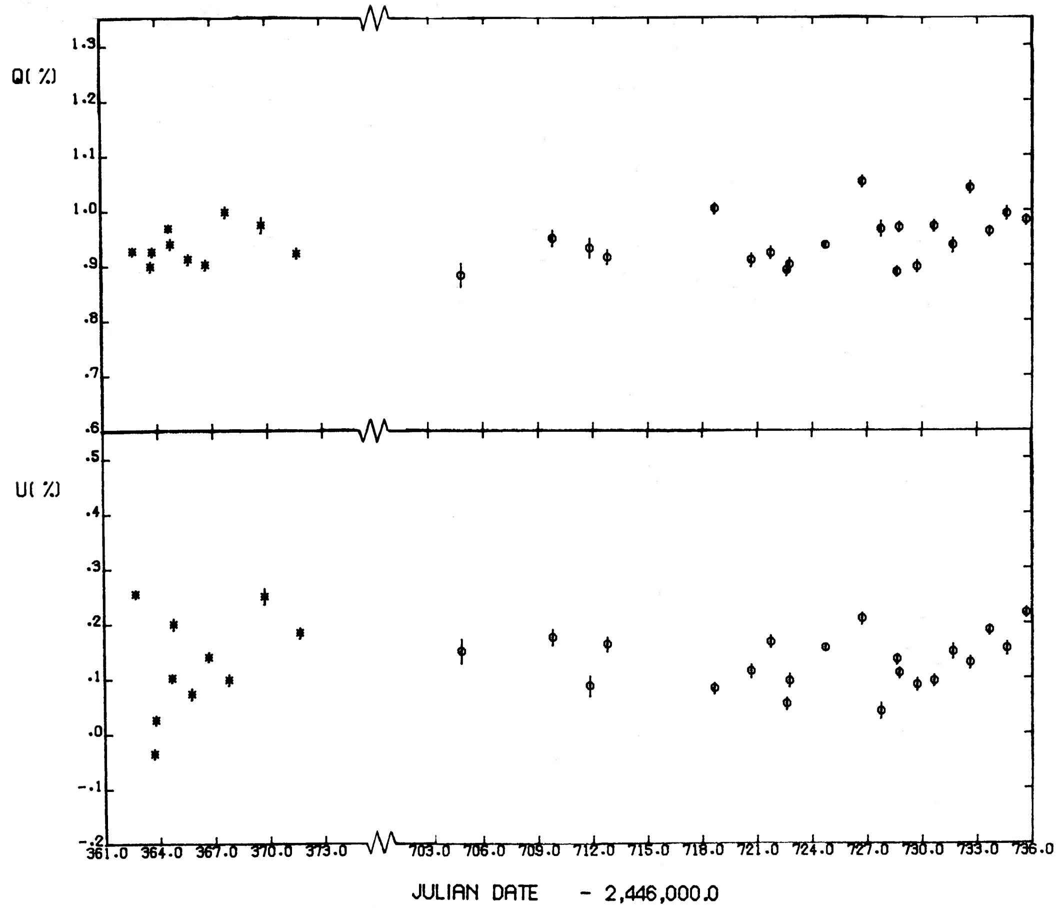

FIG. 7.—Stokes parameters Q and U plotted as a function of Julian Date for HD 191765. Symbols are as in Fig. 2.

envelope). Among the Cygnus WR stars (excluding the two binaries V444 Cyg and HD 190918), HD 191765 is the object for which such a plane is the most evident (see Fig. 8). Nevertheless, the degree of flattening is weak, depending on only a few isolated data points. Polarimetric observations of HD 93162 (Paper II) are also confined in a preferred plane

TABLE 10

AVERAGE LINEAR POLARIZATION VALUES FOR HD 192163

Reference	Mean JD	Filter	$\bar{P}^a$	$\bar{\theta}^b$	n
Hall 1958	≃2,433,284	No	1.9%	173°	?
Coyne 1974	2,440,416	B^c	1.51	178.4	2
Coyne 1974	2,446,366	B^c	1.46	177.3	1
1984, Mount Lemmon ..... and Mount Bigelow	2,445,977	*B*	1.448 (0.025)	177.8	12
1984, OMM	2,446,006	*B*	1.435 (0.035)	177.5	9
1985, Mount Lemmon ..... and Mount Bigelow	2,446,366	*B*	1.441 (0.040)	177.2	8
1986, Mount Lemmon	2,446,724	*B*	1.454 (0.022)	177.4	30

[a] Same as in Table 4.
[b] Same as in Table 4.
[c] Same as note (d) in Table 4.

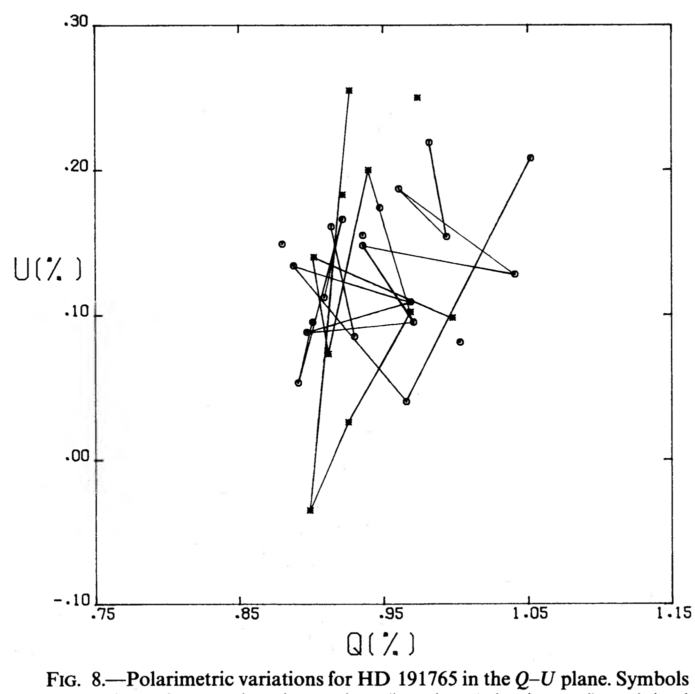

FIG. 8.—Polarimetric variations for HD 191765 in the Q–U plane. Symbols are as in Fig. 2. Consecutive observations (less than 1 day interval) are joined by a line.

TABLE 11

LINEAR POLARIZATION DATA FOR HD 191765

Julian Date (2,446,000+)	P	σ_p	θ	σ_θ	Q	U	Source[a]
362.717.........	0.962%	0.007%	187°7	0°2	0.927%	0.255%	1
363.702.........	0.900	0.009	178.9	0.3	0.899	−0.035	1
363.775.........	0.926	0.008	180.8	0.2	0.926	0.026	1
364.687.........	0.974	0.007	183.0	0.2	0.969	0.102	1
364.789.........	0.961	0.010	186.0	0.3	0.940	0.200	1
365.758.........	0.915	0.010	182.3	0.3	0.912	0.073	1
366.691.........	0.913	0.009	184.4	0.3	0.902	0.140	1
367.789.........	1.003	0.010	182.8	0.3	0.998	0.098	1
369.745.........	1.006	0.015	187.2	0.4	0.974	0.250	1
371.703.........	0.940	0.010	185.6	0.3	0.922	0.183	1
704.805.........	0.892	0.022	184.8	0.7	0.880	0.149	2
709.780.........	0.964	0.015	185.2	0.4	0.948	0.174	2
711.805.........	0.934	0.018	182.6	0.6	0.930	0.085	2
712.781.........	0.928	0.013	185.0	0.4	0.914	0.161	2
718.652.........	1.006	0.010	182.3	0.3	1.003	0.081	2
720.652.........	0.916	0.012	183.5	0.4	0.909	0.112	2
721.713.........	0.937	0.011	185.1	0.3	0.922	0.166	2
722.609.........	0.893	0.011	181.7	0.4	0.891	0.053	2
722.749.........	0.906	0.012	183.0	0.4	0.901	0.095	2
724.717.........	0.949	0.006	184.7	0.2	0.936	0.155	2
726.727.........	1.072	0.010	185.6	0.3	1.052	0.208	2
727.764.........	0.967	0.014	181.2	0.4	0.966	0.040	2
728.626.........	0.898	0.009	184.3	0.3	0.888	0.134	2
728.735.........	0.975	0.009	183.2	0.3	0.969	0.109	2
729.713.........	0.901	0.011	182.8	0.3	0.897	0.088	2
730.654.........	0.976	0.010	182.8	0.3	0.971	0.095	2
731.676.........	0.948	0.013	184.5	0.4	0.936	0.148	2
732.631.........	1.049	0.011	183.5	0.3	1.041	0.128	2
733.678.........	0.979	0.009	185.5	0.3	0.961	0.187	2
734.630.........	1.006	0.012	184.4	0.3	0.994	0.154	2
735.678.........	1.006	0.009	186.3	0.3	0.982	0.219	2

[a] Sources as in Table 2.

(better defined than for HD 191765). A disk-shape envelope for HD 191765 has already been proposed by Schmidt (1988) on the basis of the unusually weak level of polarization in the emission lines, compared to the continuum. No other WR stars observed in spectropolarimetry by Schmidt (1988) show this effect as clearly as HD 191765. We conclude that, for the majority of WR stars, asymmetries tend to be formed in a more nearly spherically symmetric wind rather than a highly flattened (rotating?) disk.

d) The Single Star HD 192103 (WR 135): WC8

HD 192103 was first cataloged as a variable star, V1042 Cyg, because of its photometric variations (Ross 1961). Between 1969 and 1973, Cherepashchuk (1975*b*) confirmed the variable nature of the star. The emission-line profiles, studied by Schumann and Seggewiss (1975), also revealed significant variations on a time scale of days and seconds. The variations were then associated with clouds in motion in an ambient, lower density stellar wind. More recently, the small amplitude of photometric variations obtained by Moffat and Shara (1986) demonstrated that HD 192103 had probably reached a quieter phase.

The radial velocities obtained from 42 spectra collected by Lamontagne (1983) gave no significant periodicity. Also, no absorption lines have been noticed in these spectra.

The polarimetric data of HD 192103, presented in Figure 9 and Table 12, reveal small fluctuations. A search for periodicity did not lead to any significant period. Thus, all observations to date suggest that HD 192103 is a single star, with small intrinsic variations probably related to asymmetric and stochastic ejection in the wind.

IV. INTRINSIC POLARIMETRIC VARIABILITY OF WR STARS

In Paper II, a correlation was found between $\sigma(P)$, the dispersion amplitude of the intrinsic polarimetric variations (excluding any orbital modulation), and spectral subtype, for 11 WR stars (polarimetric observations of these stars were studied in detail in Papers I and II). This correlation showed that the largest amplitudes of polarization are associated with late-subtypes, i.e., WC9 and WN8 stars. A correlation was also found with the terminal velocity (v_∞): fast-wind stars tend to show less scatter in polarization. These results were interpreted as the presence of blobs in the wind, which are more stable in slow winds (fast winds tend to homogenize the outflow). The origin of the blobs is still unknown; in Paper II, it was suggested that they could be the consequence of NRP in the underlying star or of instabilities arising in the line-driven wind itself.

We repeat this analysis here, using a larger sample of 26 WR stars (see Table 13). The new sample includes all stars studied in Papers I, II, and III, except, as in the original analysis, the two binaries containing a supergiant companion, γ^2 Vel and θ Mus, since their variations may be associated with NRP of the supergiant star. The sample also includes the two binaries HD 197406 (Drissen *et al.* 1986*a*) and HD 214419 (Drissen *et al.* 1986*b*), as well as the bright Cygnus WR stars analyzed here and V444 Cyg presented in Paper VI. One of the Cygnus stars,

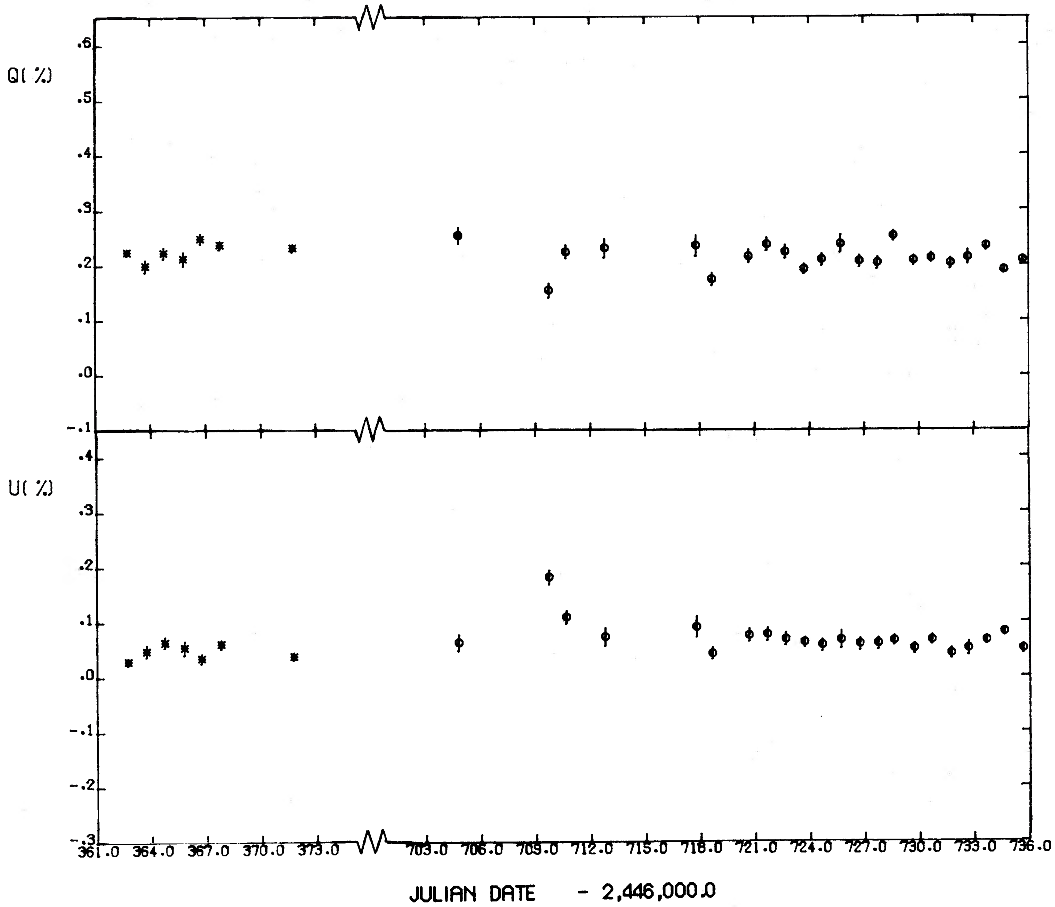

FIG. 9.—Stokes parameters Q and U plotted as a function of Julian Date for HD 192103. Symbols are as in Fig. 2.

HD 190918, also a binary with a supergiant companion, is retained in the sample, since it shows no evidence for strong variations due to the supergiant companion, as in the cases of γ^2 Vel and θ Mus. The variations observed for HD 193793 (WC7 + O4 V) and the WR + abs systems where a companion is expected are assumed to be intrinsic to the WR star, not due to orbital modulation, since the total observing interval was considerably shorter than the long periods proposed or confirmed. Variations in the suspected WR + c systems are also assumed to be associated with the WR stars only. We do not consider the WR star EZ CMa (HD 50896) in this analysis because of the difficulty in interpreting its polarimetric behavior (this peculiar object is the subject of a separate paper by Drissen *et al.* 1989). Despite these omissions, the sample is almost complete as far as covering stars of different subtypes is concerned; only hot WR stars of extreme spectral subtypes (WN2, WN3, WC4, and WO) are missing.

The parameter $\sigma(P)_{\rm net}$ given in Table 13 is the net scatter in P, as defined by equation (1), from which the average instrumental error $\bar{\sigma}_P$ has been subtracted:

$$\sigma(P)^2_{\rm net} = \sigma(P)^2 - \bar{\sigma}^2_P . \quad (4)$$

Values of $\bar{\sigma}_P$ can vary from 0.010% to 0.042%.

Figure 10 shows $\sigma(P)_{\rm net}$ versus spectral subtype for both the WC and the WN stars. As noted in Paper II, the largest dispersion tends to occur among the late subtypes of low ionization. Because the present sample includes more stars, one now sees that the WC stars are clearly located below the WN stars of the same numerical subtype (e.g., WC7 vs. WN7). This may be an artifact of the peculiar definition of the subtypes; indeed the WC–WN difference becomes less pronounced after shifting the WC data by two subclasses in the hotter direction. Part of the difference is real, however, since there is no WN star with a value of $\sigma(P)_{\rm net}$ as small as that of some of the WC stars. Furthermore, Figure 10 shows that the WN stars suspected to harbor a compact companion (*bold symbol*) are equally interspersed among the other WN stars (the WC stars include only one candidate suspected to have a compact companion). Also, the WR + O systems do not appear to differ significantly from the single WR stars after allowing for orbital modulation. Note that the sample does not include any WR + O binary composed of a late-subtype WN8, WC8, or WC9 star.

A plot (not shown) of $\sigma(P)_{\rm net}$ versus the absolute visual magnitude (M_v from van der Hucht *et al.* 1988) reveals a very similar correlation, as seen in Figure 10. This is expected from the known correlation between the WR spectral subtype and M_v (e.g., Lundström and Stenholm 1984).

Figure 11 shows the same basic correlation as found in Paper II between $\sigma(P)_{\rm net}$ and v_∞ (values of v_∞ are listed in Table 13; some of these values are at present under revision by Williams and Eenens 1989*a*, *b* and might have to be reduced by 30%–40%). The dispersion is larger for the new sample probably because it includes more stars. Again, there is a trend for slower winds to display larger amplitudes of polarimetric variation. The WC stars are not better merged here with the WN stars than in Figure 10; they are located near the lower

TABLE 12

LINEAR POLARIZATION DATA FOR HD 192103

Julian Date (2,446,000+)	P	σ_P	θ	σ_θ	Q	U	Source[a]
362.729	0.226%	0.006%	3°.7	0°.8	0.224%	0.029%	1
363.709	0.205	0.011	6.8	1.5	0.199	0.048	1
364.721	0.232	0.010	8.0	1.2	0.223	0.064	1
365.782	0.219	0.013	7.2	1.7	0.212	0.054	1
366.716	0.251	0.009	3.9	1.0	0.249	0.034	1
367.779	0.244	0.008	7.1	0.9	0.237	0.060	1
371.742	0.235	0.007	4.6	0.8	0.232	0.038	1
704.825	0.262	0.015	6.9	1.6	0.254	0.062	2
709.741	0.238	0.013	24.8	1.5	0.154	0.181	2
710.673	0.249	0.012	12.9	1.3	0.224	0.108	2
712.804	0.242	0.017	8.7	2.0	0.231	0.072	2
717.823	0.252	0.019	10.5	2.1	0.235	0.090	2
718.685	0.179	0.011	6.7	1.7	0.174	0.041	2
720.701	0.228	0.012	9.5	1.5	0.216	0.074	2
721.695	0.250	0.012	8.8	1.3	0.238	0.076	2
722.699	0.234	0.012	8.3	1.4	0.224	0.067	2
723.715	0.203	0.009	8.8	1.2	0.193	0.061	2
724.702	0.217	0.011	7.5	1.4	0.210	0.056	2
725.720	0.248	0.016	7.7	1.8	0.239	0.066	2
726.751	0.215	0.011	7.8	1.4	0.207	0.058	2
727.750	0.212	0.011	8.1	1.4	0.204	0.059	2
728.638	0.261	0.009	7.2	1.0	0.253	0.065	2
729.730	0.214	0.009	6.7	1.2	0.208	0.050	2
730.673	0.223	0.009	8.6	1.1	0.213	0.066	2
731.752	0.207	0.010	5.7	1.3	0.203	0.041	2
732.681	0.220	0.013	6.6	1.6	0.214	0.050	2
733.692	0.243	0.008	7.8	0.9	0.234	0.065	2
734.653	0.207	0.007	11.4	1.0	0.191	0.080	2
735.701	0.214	0.008	6.6	1.0	0.208	0.049	2

[a] Sources as in Table 2.

TABLE 13

INTRINSIC POLARIZATION VARIATIONS OF WR STARS

HD	WR	Spectral Type	$\sigma(P)_{net}$[a]	v_∞[b] (km s^{-1})	References	R_* ($R_\odot$)
86161	16	WN8(+c)	0.078%	(1200)	1	22.0
92740	22	WN7 + abs(+O)	0.042	2600	2	11.2
93131	24	WN7+abs	0.044	2900	2	11.2
93162	25	WN7+abs	0.027	2900	3	11.2
96548	40	WN8(+c)	0.154	1800	2	22.0
97152	42	WC7+O5–7	(0.014)	2800	4	2.2
151932	78	WN7	0.045	2400	2	11.2
152270	79	WC7+O5–8	(0.018)	3300	3	2.2
156385	90	WC7	0.009	3000	2	2.2
164270	103	WC9(+c)	0.064	1400	5	4.5
165763	111	WC5	0.013	3700	2	1.6
177230	123	WN8(+c)	0.128	(1200)	1	22.0
	124	WN8(+c)	0.118	1800	2	22.0
186943	127	WN4+O9	(0.036)	(2375)	6	1.5
187282	128	WN4(+c)	0.040	(2375)	6	1.5
190918	133	WN4.5+O9.5 Ia	(0.022)	1750	1	2.1
191765	134	WN6(+c)	0.043	2700	2	5.6
192103	135	WC8	0.020	2000	2	2.9
192163	136	WN6(+c)	0.024	2400	2	5.6
192461	137	WC7+abs(O?)	0.020	2700	1	2.2
193077	138	WN5+abs(O?)	0.028	1700	1	2.9
193576	139	WN5+O6	(0.030)	2500	7	2.9
193793	140	WC7+O4 V	0.031	3000	8	2.2
197406	148	WN7+c	(0.070)	(2350)	6	11.2
211853	153	WN6+O(+O+O)	(0.042)	(2284)	1	5.6
214419	155	WN7(+abs)+O	(0.096)	(2350)	6	11.2

[a] Values of $\sigma(P)_{net}$ in parentheses refer to the deviations from a binary fit.

[b] v_∞ refers to the WR component. Values in parentheses consist of an average v_∞ based on many stars of the same spectral type.

REFERENCES FOR v_∞.—(1) Abbott *et al.* 1986. (2) Willis 1982. (3) Barlow, Smith, and Willis 1981. (4) Torres, Conti, and Massey 1986. (5) van der Hucht *et al.* 1981. (6) Abbott and Conti 1987. (7) Cherepashchuk, Eaton, and Khaliullin 1984. (8) Fitzpatrick, Savage, and Sitko 1982.

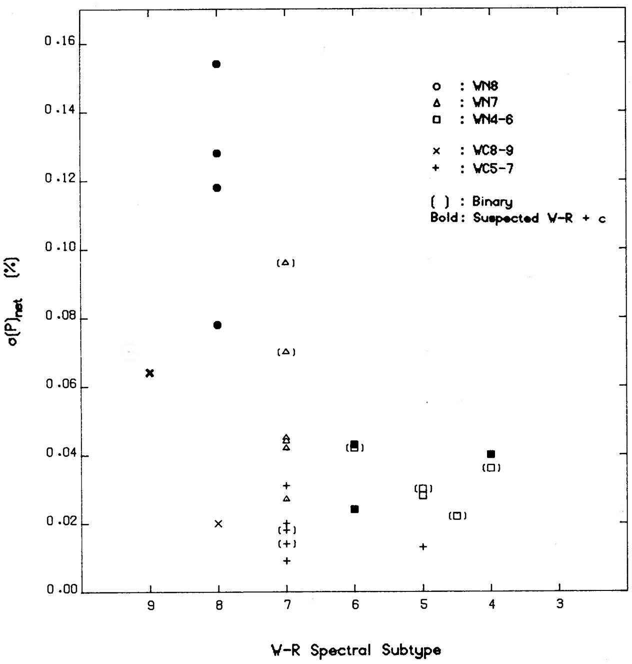

FIG. 10.—Net polarization scatter plotted as a function of *spectral subtype* for 26 WR stars (see Table 13). Late subtypes show larger amplitudes. For a given subtype, the WC stars are located generally below the WN stars. The correlation is much tighter for each spectral sequence (WN or WC) individually.

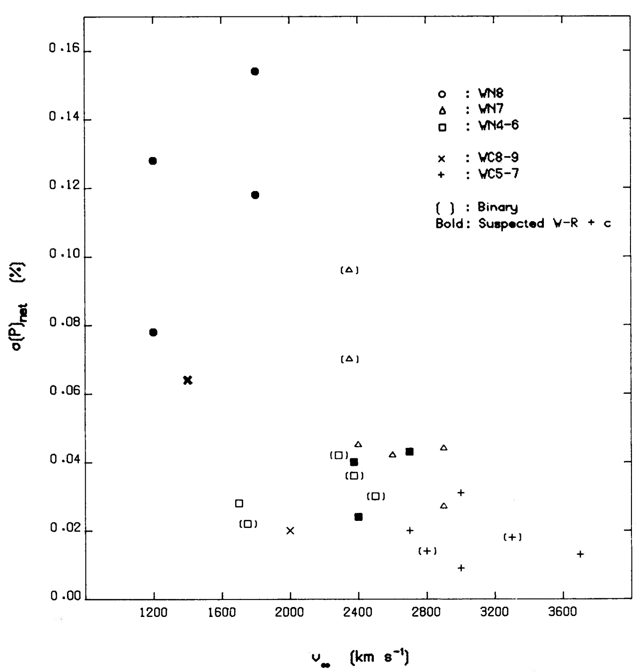

FIG. 11.—Net polarization scatter plotted as a function of *terminal velocity* for 26 WR stars (see Table 13). Stars with slow winds tend to show larger amplitudes. As in Fig. 10, WC stars are located below the WN objects. Although the correlation is fairly clear, considerable noise remains.

WN envelope in $\sigma(P)_{net}$. The overall similarity of the distributions in Figures 10 and 11 is a consequence of the loose correlation between v_∞ and spectral subtype (e.g., Smith and Willis 1983; Abbott and Conti 1987).

There appears (not shown) to be a linear correlation between $\sigma(P)_{net}$ and the mass or log $\dot{M}$ of the observed WR stars in binary systems ($\dot{M}$ is taken from the polarimetric analysis of Paper III: $\dot{M}$ and the WR mass are listed in Paper III). Nevertheless, both relations are strongly influenced by the two objects, HD 197406 and HD 214419, of large $\sigma(P)_{net}$, for which the accuracy is not high (these two stars have the largest instrumental error). The relation with log $\dot{M}$ vanishes if the values of $\dot{M}$ for all observed WR stars are taken from the radio work of Abbott *et al.* (1986) or Barlow, Smith, and Willis (1981). The ionization coefficient (C_5 of Abbott *et al.* 1986 or van der Hucht, Cassinelli, and Williams 1986) and the X-ray luminosity (Pollock 1987) have been compared to $\sigma(P)_{net}$ without showing any significant correlation. Other potentially useful parameters, such as the radius and opacity of the extended stellar envelope or the rotational velocity of the WR star, are not known well enough yet to allow a meaningful correlation search with $\sigma(P)_{net}$.

The existence of small fluctuations on time scales of hours to days, in line profiles, in photometry, and now in polarimetry, poses a new challenge not to be ignored in models of WR winds. Theoreticians now agree to the necessity of including instabilities in the wind models of hot stars to account for the observed intrinsic variations. These instabilities are described in a general way as small perturbations growing with time, inducing significant deviations from the original state (Appenzeller 1985). A good summary of the work done on radiatively driven instabilities is presented by Rybicki (1987). He describes in some detail the strongest dominating instability of this type, the line-shape instability. The linear theory for this kind of instability predicts growth rates of order of 100 *e*-folds in a typical outflow time. Numerical simulations by Owocki, Castor, and Rybicki (1988; hereafter OCR) show rarefactions of the material at highest wind speed and perhaps shells and shocks in the nonlinear regime (which can be reached fairly early in the expansion process). Originally, blob formation in an unstable, line-driven wind was proposed by Lucy and White (1980) to explain the X-ray emission of hot stars.

Among the other types of instability, great attention has been devoted to vibrational instabilities (pulsations) of radial and nonradial modes of the central star (Cox and Cahn 1988; Noels and Scuflaire 1986; Appenzeller 1985; Maeder 1985; Noels and Gabriel 1981; Simon and Stothers 1970). The numerical models of Maeder (1985) predict an unstable regime for WR stars with H/He ≤ 0.3 at their surface. This latter result now appears to be inconsistent with observations (if they are in fact related to pulsations), which show that WNL stars, with H/He ≥ 2–3, have the strongest photometric (Lamontagne and Moffat 1987) and polarimetric (this work) amplitudes. The propagation of NRP in the stellar envelopes of WR stars was also suggested by Vreux (1985) to explain the radial velocity variations of certain WR stars that were previously suspected to harbor a compact companion. On the other hand, Matthews and Beech (1987) have contested Vreux's claim for spectroscopically determined pulsations (with periodicity smaller than half a day) in WR envelopes.

Underhill (1986) has proposed that macroturbulence in the emission lines could be due to various ions circulating in magnetic loops. Be stars also display variabilities of unknown nature (NRP, rotating spots, etc.). Rotating stochastic globules have been modeled polarimetrically in Be stars by Clarke and McGale (1986 and 1987), who found a model-dependent locus in the Q–U plane. Such a locus is not obvious in the polarization data in any of the observed WR stars.

The very existence of fluctuations in polarization must be due to asymmetries in the wind. The polarimetric variations give a measure of the overall net asymmetry of the wind envelope; it would be difficult to extract any direct information about the number of asymmetric structures in the wind, let alone their sizes and lifetimes. Since a large range in polarimetric amplitude is found and there is no evidence for a cutoff in v_∞ or spectral subtype for variations to start appearing suddenly, it seems likely that the mechanism of blob formation is present in all WR stars. However, the mechanism appears to be quieter for WR stars of early subtype, and/or the blobs are partially destroyed or have less time to grow in the case of the faster stellar winds.

In a first attempt to understand the observed variations, we model the polarization dispersion according to the results of OCR for the line shape instability. This radiation instability is assumed to occur in all WR stars. We then suppose that the rarefied wind perturbation develops a bloblike structure. OCR derived a velocity-amplitude growth proportional to $e^{2.7\, v/v_{\rm th}}$ (where $v_{\rm th}$ is the thermal velocity). By analogy, we associate the polarization dispersion to a similar growth:

$$\sigma(P)_{\rm net} \propto e^{k(\bar{v}/v_{\rm th})} , \tag{5}$$

where k is taken to be a constant (close to 2.7?) for all stars and $\bar{v}$ is the mean effective velocity, assumed to correspond to the radius in the wind ($\bar{r}$) where the opacity $\tau = 1$. The general wind velocity law of Castor and Lamers (1979) gives a useful *Ansatz* for the relation between the velocity and the radius:

$$v = v_\infty\left(1 - \frac{R_*}{r}\right)^\beta , \tag{6}$$

with R_* the stellar core radius and β a constant usually between 0.5 and 1. The continuum opacity for the near side of the wind is

$$\tau = \int_{\bar{r}}^{\infty} n_e \sigma_e \, dr = 1 , \tag{7}$$

where n_e is the electron density and σ_e is the electron cross section. Assuming (*a*) spherical symmetry and (*b*) mass conservation, $\dot{M} = 4\pi r^2 v\rho =$ constant, and (*c*) the WR wind composed of totally ionized helium (i.e., $\rho = n_e m_{\rm He}/2$), then

$$n_e = \frac{\dot{M}}{2\,\pi m_{\rm He} v_\infty r^2 (1 - R_*/r)^\beta} . \tag{8}$$

For the commonly found value $\beta = 1$, the last three equations give

$$\bar{v} = v_\infty\left(1 - \frac{R_*}{\bar{r}}\right) = v_\infty e^{-3.0 \times 10^{-9}(v_\infty R_*/\dot{M})} , \tag{9}$$

where v_∞, R_*, and $\dot{M}$ are expressed in units of km s^{-1}, $R_\odot$, and $M_\odot$ yr^{-1}, respectively. Then one finds the relation:

$$\ln[\sigma(P)_{\rm net}] \propto \frac{v_\infty}{v_{\rm th}} e^{-3.0 \times 10^{-9}(v_\infty R_*/\dot{M})} . \tag{10}$$

There are considerable uncertainties in the parameters v_∞, $v_{\rm th}$, R_*, and $\dot{M}$. To compare equation (10) with the polarimetric observations, we assume that the thermal velocity is simply expressed by means of the electron temperature T_e:

$$v_{\rm th}^2 = \frac{2k_{\rm B} T_e}{m_e} , \tag{11}$$

where m_e is the electron mass and $k_{\rm B}$ is the Boltzmann constant. The electron temperatures for WR stars of different spectral type are taken from the results of Smith and Willis (1981). The stellar radii are not well known, except for the two eclipsing WN stars V444 Cyg ($R_* = 2.9\ R_\odot$ from Cherepashchuk, Eaton, and Khaliullin 1984) and HD 214419 ($R_* = 11.2\ R_\odot$ from Leung, Moffat, and Seggewiss 1983). Therefore, we simply assume a linear relation between log R_* and spectral subclass of WN stars (as one observes for other parameters such as $M_v \propto -2.5 \log L_v$ vs. subclass; see Lundström and Stenholm 1984). This assumption allows us to estimate R_* by interpolation for the other spectral subtypes. The same relation is also used for the WC stars, but with a shift in spectral subclass corresponding to the difference between the masses and the equivalent widths of lines in the WN and WC star sequences. The values so calculated for R_* are given in Table 13. The values of $\dot{M}$ used are either from Paper III, from Abbott *et al.* (1986) or from Barlow, Smith, and Willis (1981). The different plots (not presented here) of ln $[\sigma(P)_{\rm net}]$ versus the right side of equation (10) calculated with the different sources of $\dot{M}$ do not show any strong correlation. The slope (corresponding to the parameter k of eq. [5]) even changes from positive to negative according to the source of $\dot{M}$ used. Because of the large additional uncertainties in the parameters R_*, $v_{\rm th}$, and v_∞, not to mention the assumptions made, we cannot make any definite conclusion about the validity of this model to account for the observed polarization dispersion.

Out of curiosity we also try another model to explain the observations. It is based on the simple hypothesis commonly observed in nature, viz., that the instantaneous perturbation growth rate is proportional to the magnitude of the perturbation itself:

$$\frac{d\sigma(P)_{\rm net}}{dt} \propto \sigma(P)_{\rm net} . \tag{12}$$

Simple integration over the stellar envelope in which the growth occurs and is observable gives

$$\sigma(P)_{\rm net} = \sigma_0 e^{q\Delta t} , \tag{13}$$

where σ_0 is the initial amplitude of the perturbation at the base of the wind, q is a constant, and Δt is the outflow time. This latter parameter can be estimated from the parameterized wind-velocity law of Castor and Lamers (1979), integrated between two fixed radius limits where significant light scatter occurs:

$$\Delta t = \int_{aR_*}^{bR_*} \frac{dr}{v(r)} = \frac{1}{v_\infty} \int_{aR_*}^{bR_*} \frac{dr}{(1 - R_*/r)^\beta} . \tag{14}$$

With the transformation $x = rR_*^{-1}$,

$$\Delta t = \frac{R_*}{v_\infty} \int_a^b \frac{dx}{(1 - 1/x)^\beta} = \frac{R_*}{v_\infty} I . \tag{15}$$

If we assume a constant value of I for all WR stars (i.e., homologous winds differing only in scale), equation (13) then becomes

$$\sigma(P)_{\rm net} = \sigma_0 e^{q'(R_*/v_\infty)} , \tag{16}$$

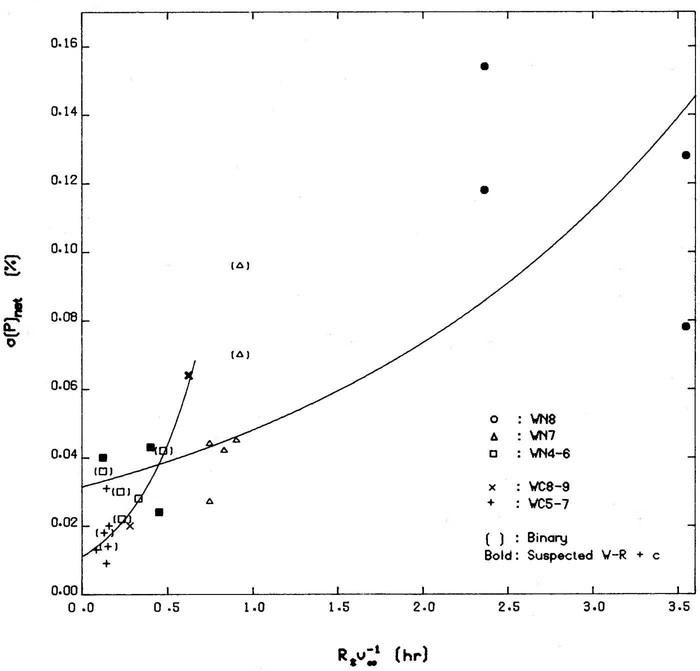

FIG. 12.—Net polarization scatter for WC and WN stars plotted vs. $R_* v_\infty^{-1}$ (see Table 13). Solid curves represent a fit of the form $\sigma(P)_{\rm net} = \sigma_0 \exp(q' R_*/v_\infty)$, where $\sigma_0 = 0.011\%$ and $q' = 2.77$ hr^{-1} for the WC stars and $\sigma_0 = 0.031\%$ and $q' = 0.43$ hr^{-1} for the WN stars.

where q' is the product of the two constants q and I. Figure 12 shows $\sigma(P)_{\rm net}$ versus $R_* v_\infty^{-1}$ for WN and WC stars, with the values for R_* and v_∞ from Table 13. The curves in Figure 12 are approximate fits to the data based on equation (16) for WC and WN stars separately. The best values of the two free parameters are $\sigma_0 = 0.011\%$ and $q' = 2.77$ hr^{-1} (correlation coefficient between $\ln[\sigma(P)_{\rm net}]$ and $R_* v_\infty^{-1}$; $r = 0.65$) for the WC stars, and $\sigma_0 = 0.031\%$ and $q' = 0.43$ hr^{-1} ($r = 0.62$) for the WN stars.

The exponential behavior predicted by this simple model may be seen in the polarization data for the WN stars for which there are more data points (Fig. 12), but again uncertainties in the stellar parameters involved in equation (16) are still a limiting factor. Also, this model is not easy to interpret physically beyond the simple assumptions made. Nevertheless, the crucial parameter appears to be the propagating time scale of the wind.

V. SUMMARY AND CONCLUSIONS

In the first part of this paper, we have presented polarimetric data for seven of the eight bright WR stars in Cygnus. These data reveal various constraints for the individual stars.

Because of incomplete phase coverage, our polarimetric monitoring of the long-period eccentric binary HD 190918 does not yield strong constraints except that the value of Ω should be close to 130°. Better determination of i, τ_*, Q_0, U_0, λ_p, and e must await further data. The supergiant O companion in HD 190918 seems to be quieter (no evidence for significant NRP) than the supergiant O companions in γ^2 Vel and θ Mus.

The polarimetric data are so far insufficient to show any orbital modulation for the long-period systems HD 193793 (WC7 + O4 V, 7.9 yr period), HD 192641 (WC7 + abs, ~12 yr period?), and HD 193077 (WN5 + abs, ~1538 day period?). HD 192641 shows the smallest polarimetric variations among all eight bright Cygnus WR stars. Polarimetric measurements for HD 192641, HD 193077, and HD 193793, obtained by other groups of observers since 1951, are very similar to the present data; the implied low amplitude of long-term polarimetric variation might be explained by a highly eccentric orbit. If so, then extensive polarimetric observations should be carried out close to the time of periastron passage when there is a greater chance of detecting a significant modulation. Except for HD 193793, this time is not well known. If the formation of dust is thought to occur, future polarimetric observations should also be repeated in different filters to allow a study of the wavelength dependence. With the present limited polarization data, the three objects of type WR + abs appear to behave like single stars.

Neither of the two WR + c candidates, HD 192163 nor HD 191765, reveals polarization variations with any of the periods found previously from photometry or spectroscopy. An independent search for periodicity among the polarization data yields, for HD 192163, a period of 7.080 days (only for the data of 1984 and 1986) and for HD 191765, a value of 1.2707 days. Neither of these inspires confidence that a true periodicity exists for these stars. The variability could possibly be due to random blob ejection, as is most likely for the single WR star in Cygnus HD 192103.

The lack of a clear preferred plane in the Q–U plot for any of the Cygnus WR stars, apart from the modulation due to binary motion, suggests that whatever is varying in the wind is distributed nearly spherically rather than in an oblate configuration.

In the second part of this paper, the polarimetric observations of the eight bright Cygnus WR stars are combined with similar data for other WR stars studied previously. The total of 26 stars covers most WN and WC subtypes with some degree of redundancy. They allow one to probe the possible source of intrinsic polarimetric variations. The dispersion of the polarization data (about the average value for a single star or about the fitted curve for a binary) is confirmed (as suggested by fewer data in Paper II) to be correlated with spectral subtype and v_∞. Late-subtype or slow-wind stars tend to show stronger variations. Also, WC stars show smaller $\sigma(P)_{\rm net}$ than WN stars of the same v_∞ and spectral subtype (e.g., WN6 vs. WC6). We argue that blobs in the WR wind are responsible for the asymmetry-induced polarization variations observed. Blobs are probably created in all WR winds but survive or grow more effectively in slow-wind than in fast-wind stars and also in WN than in WC stars.

On the basis of the work of OCR for the line-shape instability in a radiatively driven wind, we model the polarization scatter with a growth proportional to $\exp(k\bar{v}/v_{\rm th})$. The effective velocity is assumed to correspond to a position in the wind where $\tau = 1$. We find a formula relating $\sigma(P)_{\rm net}$ and the parameters v_∞, $v_{\rm th}$, R_* and $\dot{M}$. No clear correlation has been found. However, uncertainties in the stellar parameters and model assumptions may be hiding the real behavior. Therefore, we cannot conclude if the polarization scatter is caused by instabilities in a radiatively driven wind.

Another simple working model, based on the hypothesis that the perturbation growth rate is proportional to the magnitude of the perturbation itself, leads to the prediction of an exponential dependence of $\sigma(P)_{\rm net}$ on Δt, the travel time in the wind. Taking Δt proportional to $R_* v_\infty^{-1}$ in homologous winds, we find a better fit with the observations, although the stellar radius is not well known for WR stars.

Continuum linear polarimetric data alone cannot be easily used to describe a typical single blob by itself, since such data give only a global measure of the vectorial sum of all the asymmetries in the wind. One will also have to resort to high-resolution emission-line profile studies. Moffat *et al.* (1988) have recently revealed small bumps of various strengths in the emission-line profile of He II λ5411 in some of the Cygnus WN stars studied here; the bumps appear to be accelerated outward along with the general wind. Precision spectropolarimetry of many emission lines simultaneously is expected to yield valuable information concerning the propagation of these blobs and their birth location in the wind.

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REFERENCES

Abbott, D. C., Bieging, J. H., Churchwell, E., and Torres, A. V. 1986, *Ap. J.*, **303**, 239.
Abbott, D. C., and Conti, P. S. 1987, *Ann. Rev. Astr. Ap.*, **25**, 113.
Angel, J. R. P., and Landstreet, J. D. 1970, *Ap. J. (Letters)*, **160**, L147.
Annuk, K. 1988, preprint.
Antokhin, I. I., Aslanov, A. A., and Cherepashchuk, A. M. 1982, *Soviet Astr. Letters*, **8**, 156.
Antokhin, I. I., and Cherepashchuk, A. M. 1984, *Soviet Astr. Letters*, **10**, 155.
———. 1985, *Soviet Astr. Letters*, **11**, 355.
Antokhin, I. I., and Volkov, I. M. 1987, *Inf. Bull. Var. Stars*, No. 2973.
Appenzeller, I. 1985, in *IAU Symposium 116, Luminous Stars and Associations in Galaxies*, ed. C. W. H. de Loore, A. J. Willis, and P. Laskaridos (Dordrecht: Reidel), p. 139.
Aslanov, A. A., and Cherepashchuk, A. M. 1981, *Soviet Astr. Letters*, **7**, 265.
Barlow, M. J., Smith, L. J., and Willis, A. J. 1981, *M.N.R.A.S.*, **196**, 101.
Bastien, P. 1985, *Ap. J. Suppl.*, **59**, 277.
———. 1989, in *Polarized Radiation of Circumstellar Origin*, ed. G. V. Coyne *et al.* (Vatican: Vatican Observatory), p. 595.
Bastien, P., Drissen, L., Ménard, F., Moffat, A. F. J., Robert, C., and St.-Louis, N. 1988, *A.J.*, **95**, 900.
Becker, R. H., and White, R. L. 1985, *Ap. J.*, **297**, 649.
Bracher, K. 1966, Ph.D. thesis, Indiana University.
Brown, J. C., Aspin, C., Simmons, J. F. L., and McLean, I. S. 1982, *M.N.R.A.S.*, **198**, 787.
Castor, J. I., and Lamers, H. J. G. L. M. 1979, *Ap. J. Suppl.*, **39**, 481.
Cherepashchuk, A. M. 1975*a*, *Soviet Astr.*, **19**, 157.
———. 1975*b*, *Soviet Ap.*, **10**, 218.
Cherepashchuk, A. M., Eaton, J. A., and Khaliullin, Kh. F. 1984, *Ap. J.*, **281**, 774.
Clarke, D., and McGale, P. A. 1986, *Astr. Ap.*, **169**, 251.
———. 1987, *Astr. Ap.*, **178**, 294.
Conti, P. S., Roussel-Dupré, D., Massey, P., and Rensing, M. 1984, *Ap. J.*, **282**, 693.
Cox, A. N., and Cahn, J. H. 1988, *Ap. J.*, **326**, 804.
Coyne, G. V. 1974, *A.J.*, **79**, 565.
Drissen, L., Lamontagne, R., Moffat, A. F. J., Bastien, P., and Séguin, M. 1986*a*, *Ap. J.*, **304**, 188.
Drissen, L., Moffat, A. F. J., Bastien, P., and Lamontagne, R. 1986*b*, *Ap. J.*, **306**, 215.
Drissen, L., Robert, C., Lamontagne, R., Moffat, A. F. J., St.-Louis, N., van Weeren, N., and van Genderen, A. M. 1989, *Ap. J.*, **343**, 426.
Drissen, L., St.-Louis, N., Moffat, A. F. J., and Bastien, P. 1987, *Ap. J.*, **322**, 888 (Paper II).
Fitzpatrick, E. L., Savage, B. D., and Sitko, M. L. 1982, *Ap. J.*, **256**, 578.
Florkowski, D. R. 1982, in *IAU Symposium 99, Wolf-Rayet Stars: Observations, Physics, Evolution*, ed. C. W. H. de Loore and A. J. Willis (Dordrecht: Reidel), p. 63.
Florkowski, D. R., and Gottesman, S. T. 1977, *M.N.R.A.S.*, **179**, 105.
Fraquelli, D. A., Bolton, C. T., and Horn, J. 1987, private communication (FBH).
Frecker, J. E., and Serkowski, K. 1965, *Appl. Optics*, **15**, 605.
Hackwell, J. A., Gehrz, R. D., and Grasdalen, G. L. 1979, *Ap. J.*, **234**, 133.
Hackwell, J. A., Gehrz, R. D., and Smith, J. R. 1974, *Ap. J.*, **192**, 383.
Hackwell, J. A., Gehrz, R. D., Smith, J. R., and Stecker, D. W. 1976, *Ap. J.*, **210**, 137.
Hall, J. S. 1958, *Pub. US Naval Obs.*, **17**, 271.
Heckathorn, J. N., Bruhweiler, F. C., and Gull, T. R. 1982, *Ap. J.*, **252**, 230.
Hiltner, W. A. 1951, *Ap. J.*, **114**, 241.
Johnson, H. M., and Hogg, D. E. 1965, *Ap. J.*, **142**, 1033.
Koenigsberger, G., Firmani, C., and Bisiacchi, G. F. 1980, *Rev. Mexicana Astr.*, **5**, 45.
Lafler, J., and Kinman, T. D. 1965, *Ap. J. Suppl.*, **11**, 216.
Lamontagne, R. 1983, Ph.D. thesis, Université de Montréal.
Lamontagne, R., Moffat, A. F. J. 1987, *A.J.*, **94**, 1008.
Lamontagne, R., Moffat, A. F. J., Koenigsberger, G., and Seggewiss, W. 1982, *Ap. J.*, **253**, 320.
Leung, K.-C., Moffat, A. F. J., and Seggewiss, W. 1983, *Ap. J.*, **265**, 961.
Lozinskaya, T. A. 1980, *Soviet Astr. Letters*, **6**, 193.
Lucy, L. B., and White, R. L. 1980, *Ap. J.*, **241**, 300.
Lundström. I., and Stenholm, B. 1984, *Astr. Ap. Suppl.*, **58**, 163.
Maeder, A. 1985, *Astr. Ap.*, **147**, 300.
Massey, P. 1980, *Ap. J.*, **236**, 526.
Massey, P., Conti, P. S., and Niemela, V. S. 1981, *Ap. J.*, **246**, 145.
Matthews, J. M., and Beech, M. 1987, *Ap. J.*, **313**, L25.
Moffat, A. F. J., Drissen, L., Lamontagne, R., and Robert, C. 1988, *A.J.*, **334**, 1038.
Moffat, A. F. J., Lamontagne, R., Shara, M. M., and McAlister, H. A. 1986, *A.J.*, **91**, 1392.
Moffat, A. F. J., Lamontagne, R., Williams, P. M., Horn, J., and Seggewiss, W. 1987, *Ap. J.*, **312**, 807.
Moffat, A. F. J., and Shara, M. M. 1986, *A.J.*, **92**, 952.
Nemec, A. F. L., and Nemec, J. M. 1985, *A.J.*, **90**, 2317.
Noels, A., and Gabriel, M. 1981, *Astr. Ap.*, **101**, 215.
Noels, A., and Scuflaire, R. 1986, *Astr. Ap.*, **161**, 125.
Owocki, S. P., Castor, J. I., and Rybicki, G. B. 1988, *Ap. J.*, **335**, 914 (OCR).
Pollock, A. M. T. 1987, *Ap. J.*, **320**, 283.
Robert, C., Moffat, A. F. J., Bastien, P., St.-Louis, N., and Drissen, L. 1989, in preparation (Paper VI).
Ross, L. W. 1961, *Pub. A.S.P.*, **73**, 354.
Rybicki, G. B. 1987, in *Instabilities in Luminous Early Type Stars*, ed. H. J. G. L. M. Lamers and C. W. H. de Loore (Dordrecht: Reidel), p. 175.
Schmidt, G. D. 1988, in *Polarized Radiation of Circumstellar Origin*, ed. G. V. Coyne *et al.* (Vatican: Vatican Observatory), p. 641.
Schumann, J. D., and Seggewiss, W. 1975, in *IAU Symposium 67, Variable Stars and Stellar Evolution*, ed. V. E. Sherwood and L. Plant (Dordrecht: Reidel), p. 299.
Simmons, J. F. L., and Boyle, C. B. 1984, *Astr. Ap.*, **134**, 368.
Simon, N. R., and Stothers, R. 1970, *Astr. Ap.*, **6**, 183.
Smith, L. J., and Willis, A. J. 1983, in *Wolf-Rayet Stars: Progenitors of Supernovae?*, ed. M. C. Lortet and A. Pitault (Obs. de Meudon), p. III. 79.
———. 1981, in *IAU Symposium 99, Wolf-Rayet Stars: Observations, Physics, Evolutions*, ed. C. W. H. de Loore and A. J. Willis (Dordrecht: Reidel), p. 113.
St.-Louis, N., Drissen, L., Moffat, A. F. J., Bastien, P., and Tapia, S. 1987, *Ap. J.*, **322**, 870 (Paper I).
St.-Louis, N., Moffat, A. F. J., Drissen, L., Bastien, P., and Robert, C. 1988, *Ap. J.*, **330**, 286 (Paper III).
Torres, A. V., Conti, P. S., and Massey, P. 1986, *Ap. J.*, **300**, 379.
Treffers, R. R., and Chu, Y.-H. 1982, *Ap. J.*, **254**, 569.
Underhill, A. B. 1986, *Pub. A.S.P.*, **98**, 897.
van der Hucht, K. A., Cassinelli, J. P., and Williams, P. M. 1986, *Astr. Ap.*, **168**, 111.
van der Hucht, K. A., Conti, P. S., Lundström, I., and Stenholm, B. 1981, *Space Sci. Rev.*, **28**, 227.
van der Hucht, K. A., Hidayat, B., Admiranto, A. G., Supelli, K. R., and Doom, C. 1988, *Ap. J.*, **199**, 217.
Vreux, J.-M. 1985, *Pub. A.S.P.*, **97**, 274.
Vreux, J.-M., Andrillat, V., and Gosset, E. 1985, *Astr. Ap.*, **149**, 337.
Wendker, H. J., Smith, L. F., Israel, F. P., Habing, H. J., and Dickel, H. R. 1975, *Astr. Ap.*, **42**, 173.
Williams, P. M., Beattie, D. H., Lee, T. J., Steward, J. M., and Antonopoulov, E. 1978, *M.N.R.A.S.*, **185**, 467.
Williams, P. M., and Eenens, P. R. J. 1989*a*, in *IAU Symposium 113, Physics of Luminous Blue Variables*, ed. K. Davidson, H. J. G. L. M. Lamers, and A. F. J. Moffat (Dordrecht: Kluwer), in press.
———. 1989*b*, *M.N.R.A.S.*, submitted.

Williams, P. M., Longmore, A. J., van der Hucht, K. A., Talevera, A., Wansteker, W. M., Abbott, D. C., and Telesco, C. M. 1985, *M.N.R.A.S.*, **215**, 23.
Williams, P. M., van der Hucht, K. A., and Thé, P. S. 1987, *Quart. J.R.A.S.*, **28**, 248.
Williams, P. M., van der Hucht, K. A., van der Woerd, H., Wamsteker, W. M., Geballe, T. R., Garmany, C. D., and Pollock, A. M. T. 1987, in *Instabilities in Luminous Early Type Stars*, ed. H. J. G. L. M. Lamers and C. W. H. de Loore (Dordrecht: Reidel), p. 221.
Willis, A. J. 1982, *M.N.R.A.S.*, **198**, 897.
Wilson, O. C. 1949, *Ap. J.*, **109**, 76.

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