THE ASTROPHYSICAL JOURNAL, 330:286–304, 1988 July 1

POLARIZATION VARIABILITY AMONG WOLF-RAYET STARS. III. A NEW WAY TO DERIVE MASS-LOSS RATES FOR WOLF-RAYET STARS IN BINARY SYSTEMS

NICOLE ST.-LOUIS,[1] ANTHONY F. J. MOFFAT,[1] LAURENT DRISSEN,[1] PIERRE BASTIEN,[1] AND CARMELLE ROBERT[1]
Département de Physique, Université de Montréal
Received 1987 August 10; accepted 1987 December 22

ABSTRACT

We present new results from the polarimetric monitoring of two W-R + O binaries (HD 186943 and HD 211853) and three suspected low-amplitude single-line binaries (HD 177230, 209 BAC, and HD 187282). From these and other data, we derive mass-loss rates ($\dot{M}$) for ten W-R stars in massive binaries on the basis of the amplitude of the systematic phase-dependent modulation in linear polarization. The advantage over other independent methods of estimating the mass-loss rates lies in the relatively simple physics involved, i.e., polarization by scattering of companion-star light off free electrons in the strongly ionized interior region of the W-R wind. Neglecting possible systematic effects, the rates derived are estimated to be accurate typically to within $\pm 40\%$; where the mass-loss rates for particular stars have been determined by other means, our rates agree reasonably well with the rates obtained by the most reliable of these other means.

True stellar masses can now be estimated from the orbital inclinations derived on the basis of the polarization data themselves. These lead to a correlation of $\dot{M}$ with the mass of the W-R star, as proposed by Abbott *et al.* 1986.

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

I. INTRODUCTION

Wolf-Rayet (W-R) stars are hot, luminous, evolved objects which are characterized by their very high mass-loss rates ($\dot{M} = [0.8\text{–}8.0] \times 10^{-5}\ M_{\odot}\ \text{yr}^{-1}$; Abbott and Conti 1987). These mass-loss rates are believed to be most accurately determined via free-free emission at radio wavelengths. This radiation originates at very large radii, typically several $10^2\ R_{\odot}$, where the wind has most certainly reached the (easily determinable) terminal velocity. Nevertheless, some nagging uncertainties remain with the interpretation of the radio data, such as the degree of ionization for various elements in the outer part of the wind (see van der Hucht, Cassinelli, and Williams 1986). Thus, it should be interesting to compare this method with other methods that are relatively impervious to this uncertainty.

In this paper we present a new method for deriving the mass-loss rate in the case where the W-R star is located in a binary system. This new method involves the variation of linear polarization, described by the two Stokes parameters Q and U, as a function of orbital phase. At the root of the linear polarization is Thomson scattering of photons originating from the companion by the free electrons in the W-R wind. Light from different parts of the W-R star itself will also be polarized, but the net polarization is assumed to cancel out due to spherical symmetry. (Nonsphericity could yield a *constant*, nonzero component of polarization; also, *randomly* varying inhomogeneities could give rise to a variable component of polarization. Neither of these will affect the basic interpretations for binaries studied in this paper.) The phase-dependent modulation of the linear polarization is due to the relative orbiting motion of the companion. A model for such variations in binary systems has been developed by several authors, as described by St.-Louis *et al.* (1987, hereafter Paper I). It is assumed that (1) the envelope is optically thin, (2) the envelope is corotating, and (3) the stars are point sources moving in circular orbits. The model yields the orbital inclination, i, and other parameters characterizing the distribution of scattering matter in the system. In this paper, we will refer to this theory as the *polarization model of binary stars*.

II. MASS-LOSS RATES FROM BINARY POLARIZATION MODULATIONS

In the Q-U plane, well-behaved binary systems generally describe a double loop for one orbital revolution in the form of an ellipse. As noted by Brown, McLean, and Emslie (1978, hereafter BME), the semimajor axis (A_p) of this ellipse can be written in terms of the third and fourth density moments ($\tau_0 \gamma_3$, $\tau_0 \gamma_4$) as $A_p = \tau_0 H(1 + \cos^2 i)$, where $H^2 = \gamma_3^2 + \gamma_4^2$. If we make the physically plausible assumption that the electrons are mainly distributed with spherical symmetry around the fast-wind W-R star, we can set $\gamma_4 = 0$. The more complicated, perturbed case, where the scattering material is concentrated in a direction within the orbital plane other than that associated with the W-R star, or where there is a lack of symmetry about the orbital plane, will not be considered in this paper. Using the value of $\tau_0 \gamma_3$ given by BME, the expression for A_p becomes

$$A_p = (1 + \cos^2 i)(3\sigma_t/32\pi) f_c \int_0^{\infty}\int_0^{\pi}\int_0^{2\pi} \{n \sin^2 \theta \cos 2\phi\} dR \times \sin \theta \, d\theta \, d\phi \,, \quad (1)$$

where $\sigma_t = 6.65 \times 10^{-25}$ cm^2 is the nonrelativistic Thomson scattering cross section for a single electron, f_c is the fraction of the total light coming from the companion star, $n = n(R, \theta, \phi)$ is the electron density, and R, θ, and ϕ are corotating spherical coordinates *centered on the companion* such that the W-R star is centered at $R = a$, $\theta = \pi/2$, and $\phi = 0$.

In order to apply this equation to find the mass-loss rate of

[1] Visiting Astronomer, University of Arziona Observatories.

the W-R component, $\dot{M}$, we develop an expression for the electron density. We neglect the mass loss of the companion and distortions of the W-R wind and use the mass conservation law with spherical symmetry $\dot{M} = 4\pi R'^2 \rho(R')v(R')$, where $\rho(R')$ and $v(R')$ refer to the radial density and velocity laws of the W-R wind. We thus find a simple expression for the electron density,

$$n(R') = \frac{\alpha\rho(R')}{m_p} = \frac{\alpha\dot{M}}{4\pi m_p R'^2 v(R')} \tag{2}$$

for $R' \geq R_*$ (the W-R core radius, i.e., where $v(R') \to 0$); otherwise $n(R') = 0$, where the number of free electrons per nucleon is given by $\alpha = \Sigma F_i Z_i/N_i$, with, for the ith ion, F_i equal to the fractional abundance by mass, N_i equal to the number of nucleons in the nucleus, and Z_i equal to the number of free electrons per ion. Also, m_p is the mass of the proton, and $R' = R'(R, \theta, \phi)$ is the radial distance *from the center of the W-R star*. (Note that primed coordinates are measured relative to the W-R star while unprimed coordinates originate at the companion star.)

Supposing that the envelope consists mainly of He and that He is completely ionized in the part of the wind that concerns us ($F_{\rm He} = 1$, $N_{\rm He} = 4$, $Z_{\rm He} = 2$, i.e., $\alpha = 0.5$)—see Schmutz and Hamann (1986)—and substituting equation (2) into equation (1), the amplitude A_p can now be expressed as

$$A_p = (1 + \cos^2 i)\frac{3\sigma_t f_c \dot{M}}{(16\pi)^2 m_p}\int_0^\infty \int_0^\pi \int_0^{2\pi} \frac{\sin^3\theta \cos 2\phi}{R'^2 v(R')}\, dR\, d\theta\, d\phi \tag{3}$$

evaluated for $R' \geq R_*$ and neglecting the part of the wind not seen by the companion. Note that other common ions in W-R winds (e.g., N IV, C IV, O V,...) yield similar values of α, close to 0.5.

Observations of the variation in linear polarization yield A_p and i (see BME), while f_c can be obtained from the spectral types. Thus, with a wind velocity $v(R')$, evaluation of the integral yields an estimate for the W-R star mass-loss rate ($\dot{M}$).

We have recently analyzed five W-R binaries with the polarization model of binary stars in order to deduce the inclination of the orbital plane from the characteristic Q-U locus described by the following massive binary systems: HD 197406, WN7 (Drissen *et al.* 1986*a*); HD 214419 (CQ Cep), WN7 + O (Drissen *et al.* 1986*b*); and HD 68273, WC8 + O9I; HD 97152, WC7 + O5–7; and HD 152270, WC7 + O5–8 (Paper I). Three other W-R stars are presently being investigated: HD 190918, WN4.5 + O9.5Ia, and HD 193576, WN5 + O6, in a study of the polarization variations of the eight W-R stars in Cygnus, by Robert *et al.* (1988*a*), and the Southern WN6 + O5 binary HDE 311884, by Robert *et al.* (1988*b*) with preliminary results given by Moffat and Seggewiss (1987). Note that some of those systems have been studied previously with less precise data. In an attempt to provide a larger sample to test our new method of deriving mass-loss rates, we present in this paper new polarization data for five other W-R binaries: two double-line binaries with O-type companions, HD 186943, WN4 + O9, and HD 211853 (GP Cep), WN6 + O, along with three suspected single-line bnaries, HD 177230, WN8, 209 BAC, WN8, and HD 187282, WN4. All spectral types above and "WR" numbers used elsewhere in this paper are from the catalog of van der Hucht *et al.* (1981).

In § III, the observations and results for the five new W-R binaries analyzed in this paper will be presented, and in § IV the mass-loss rates for all the systems analyzed to date will be deduced and compared with results obtained by other methods. A summary is given in § V.

III. NEW OBSERVATIONS AND RESULTS FOR FIVE W-R BINARIES

The data for the five W-R binaries presented in this paper were obtained with the University of Arizona Minipol polarimeter during four different observing runs and using three different telescopes of the University of Arizona, as indicated in the tables. All the observations were secured using a blue Corning filter which has a FWHM bandpass of 1800 Å and is centered at 4700 Å. Further details of the observing procedure can be found in Paper I.

a) Double-Line Binaries

i) *HD 186943 = WR 127* (WN4 + O9.5V)

The polarimetric observations for this star (revised spectral type by Massey 1981) are presented in Table 1. The columns give the Julian date, the degree of polarization P and the associated mean error σ_p in percent, the position angle of the polarization vector Θ and its mean error σ_θ in degrees, the two Stokes parameters Q and U in percent, the orbital phase ϕ, and the observing run during which the data were obtained. The orbital phase has been calculated using the period $P = 9.5550 \pm 0.0002$ days and the origin of phase when the W-R star passes in front $E_0 = $ JD 2,443,789.45 $\pm$ 0.07 (Massey 1981). Adopting a minimum mass for the O star, Massey (1981) predicted that the system should eclipse. A restricted number of ultraviolet observations by Hutchings and Massey (1983) indeed show small depressions in the continuum and in the lines near phase 0.0. Moreover, optical photometric observations in the B band by Moffat and Shara (1986) also show a small depression at phase 0.0 ($\Delta B \approx 0.03$ mag). These are, however, not real stellar eclipses, but are rather the result of systematically varying extinction of the light from the companion as it orbits within the wind of the W-R star.

Figure 1 shows the variations of the two Stokes parameters Q and U as a function of the orbital phase. The solid curve represents the best fit of a Fourier series up to second-order harmonics according to the polarization model of binary stars. The coefficients of this fit are given in Table 2. We note the predominance of the second-order terms (q_3, u_3, q_4, u_4), indicating that the envelope is corotating. The standard deviations from the curve ($\sigma_Q[O - C] = 0.041\%$, $\sigma_U[O-C] = 0.057\%$) slightly exceed the instrumental uncertainties ($\sigma_{\rm inst} = 0.023\%$), implying the presence of some intrinsic scatter. The double loop in the Q-U plane, characteristic of binary systems (see Paper II), is shown in Figure 2.

Various parameters describing the distribution of matter in the envelope can be calculated as in Paper I using the coefficients of the fitted curve in Figure 1. These include the inclination i of the orbital plane, the angle Ω in the Q-U plane between the major axis of the (Q_+, U_+) locus (based on second harmonic terms only, for Q and U) and the celestial north pole, the four moments over the density distribution ($\tau_0\gamma_1$, $\tau_0\gamma_2$, $\tau_0\gamma_3$, and $\tau_0\gamma_4$), as well as three relevant ratios based on these moments (see Paper I). These parameters can be found in Table 3. The inclination that results is $i = 55^\circ.7 \pm 8^\circ.2$, where the error has been calculated by the method of propagation of

TABLE 1

LINEAR POLARIZATION DATA FOR HD 185943 = WR 127

Julian Date (2,440,000+)	P (%)	σ_p (%)	θ	σ_θ	Q (%)	U (%)	ϕ	Observations[a]
5966.726.........	0.960	0.043	22°6	0°5	0.676	0.681	0.873	1
5967.795.........	0.983	0.041	25.0	0.5	0.632	0.753	0.985	1
5971.640.........	1.048	0.026	22.2	0.5	0.749	0.733	0.387	1
5980.729.........	1.114	0.017	21.9	0.5	0.804	0.771	0.339	1
5981.705.........	1.005	0.025	24.4	0.5	0.662	0.756	0.441	1
5982.693.........	0.903	0.015	22.7	0.5	0.634	0.643	0.544	1
5983.701.........	0.916	0.018	19.4	0.5	0.714	0.574	0.650	1
6213.790.........	1.018	0.025	18.9	0.5	0.804	0.624	0.730	2
6219.710.........	1.201	0.031	24.1	0.5	0.800	0.896	0.350	2
6362.678.........	1.119	0.017	19.4	0.4	0.872	0.701	0.312	3
6363.670.........	1.073	0.013	23.2	0.3	0.740	0.777	0.416	3
6364.658.........	0.936	0.022	23.2	0.7	0.645	0.678	0.520	3
6365.715.........	0.934	0.019	20.6	0.6	0.703	0.615	0.630	3
6366.652.........	1.004	0.016	16.0	0.5	0.851	0.532	0.728	3
6367.709.........	1.088	0.023	18.7	0.6	0.872	0.667	0.839	3
6369.681.........	0.870	0.019	21.9	0.6	0.628	0.602	0.045	3
6371.659.........	1.007	0.018	17.7	0.5	0.821	0.583	0.252	3

[a] (1) 1984 October 5–25 at Mount Bigelow (155 cm) and Mount Lemmon (152 cm); (2) 1985 May 27–June 5 at Mount Bigelow (155 cm); (3) 1985 October 23–November 1 at Mount Bigelow (155 cm) and Mount Lemmon (152 cm and 102 cm).

errors.[2] Adopting this value of the inclination and the results obtained by Massey (1981),

$$M(\text{W-R}) \sin^3 i = 9.3 \pm 0.9 \; M_\odot ,$$

$$M(\text{O}) \sin^3 i = 19.7 \pm 3.0 \; M_\odot ;$$

we find for the masses of the stars,

$$M(\text{W-R}) = 16 \pm 5 \; M_\odot ,$$

$$M(\text{O}) = 35 \pm 11 \; M_\odot ,$$

where the uncertainties have been calculated by the method of propagation of errors.

Within its error limit, the mass of the O-star component is compatible with its spectral type. The lack of true stellar eclipses, yet the presence of significant photometric and radial velocity modulation, is compatible with the above estimate for i.

The value of the parameter A in Table 3 is high, which tells us that the electrons are symmetric about, and concentrated near, the orbital plane. The ratio γ_4/γ_3 indicates the direction of concentration of the scattering matter in the orbital plane. This value yields $\lambda_2 = -13°$ or $77° \pm 11°$; the former value is compatible with the electrons being associated with the W-R star.

The polarization vectors of the stars seen in the line of sight close to HD 186943 have been examined in an attempt to constrain the contribution of interstellar polarization (see Paper I for method). Unfortunately, there are too few stars in the region around HD 186943 (four stars to within a radius of 2° on the sky and within ± 1 of its distance modulus; including stars of *all* distances increases the sample size but degrades the scatter) for this to be meaningful.

ii) *HD 211853 = WR 153 = GP Cep* ([WN6 + O_1] + [O_2 + O_3])

The analysis of the spectroscopic observations of HD 211853 reveals that this system is quadruple. HD 211853 consists of two pairs of close binaries separated from each other by a relatively large distance; one pair is of type WN6 + O and the other O + O (see Massey 1981). The photometric data obtained by Moffat and Shara (1986) clearly show the two periods found by Massey ($P_{\text{WR}+\text{O}_1} = 6.6884$ days and $P_{\text{O}_2+\text{O}_3} = 3.4698$ days). Our polarimetric observations for HD 211853 are presented in Table 4 and in Figure 3. As expected, the polarization variations are dominated by the period characterizing the W-R + O system. The O + O system is probably much too far away to cause a modulation of the W-R star's polarization, but still could show some smaller variations of its own (however, nothing was seen with the 3.47 day period). The orbital phase has been calculated using the period $P = 6.6884 \pm 0.0001$ days and the origin of phase when the W-R star passes in front $E_0 = \text{JD } 2{,}443{,}690.32 \pm 0.07$ (Massey 1981). The fitted curve is a Fourier series up to second-order

[2] Aspin, Simmons, and Brown (1981, hereafter ASB) have presented a different method of estimating the uncertainty for the inclination, obtained from polarization modulation of binaries. Their method allows for the strong nonlinear coupling in determining the parameters. For small errors in the observed quantities, their method should converge to uncertainties similar to those obtained from the method of propagation of errors. However, our experience shows that the ASB-based errors are always somewhat greater than those from the law of propagation, even for small observing errors. This is illustrated by the well-observed, apparently well-behaved star HD 152270, for which there exist different independent estimates of the error in inclination: Luna (1982) finds $i_{\text{pol}} = 35° \pm 8°$ based on a subsample, or $42° \pm 10°$ using *all* of his data for HD 152270, compared with $i_{\text{pol}} = 44°.8 \pm 3°$ from the significantly less noisy data of St.-Louis *et al.* (1987). The ASB method yields an error of $\pm 5°$ in i for this star from the St.-Louis *et al.* data.

Since ASB only give maximum values of the scatter in the data relative to the amplitude necessary for an error in i of $\pm 5°$, it is difficult to generalize this to extract errors in i for any observational scatter. However, the law of error propagation appears to function well not only for the above star but for other stars as well, such as V444 Cygni: Robert *et al.* (1988*a*) find $i_{\text{pol}} = 78°.8 \pm 0°.5$ compared with $i_{\text{lc}} = 78° \pm 1°$ from an analysis of the light curve (see Cherepashchuk, Eaton, and Khaliullin 1984, hereafter CEK). On the other hand, the other well-known eclipsing system CQ Cep yields $i_{\text{pol}} + 78° \pm 1°$ from Drissen *et al.* (1986*b*) or $78°.1 \pm 1°.7$ from Piirola (1988), compared with $i_{\text{lc}} = 68°.0 \pm 0°.4$ from Leung, Moffat, and Seggewiss (1983) or $70° \pm 4°$ from Stickland *et al.* (1984). However, unlike V444 Cyg, CQ Cep shows a strongly distorted, variable light curve and is thus not an appropriate test object, although the two independent estimates of i_{pol} do agree well.

Thus, we feel fairly justified in using standard errors based on the formal application of independently propagating errors, as long as they are not excessive.

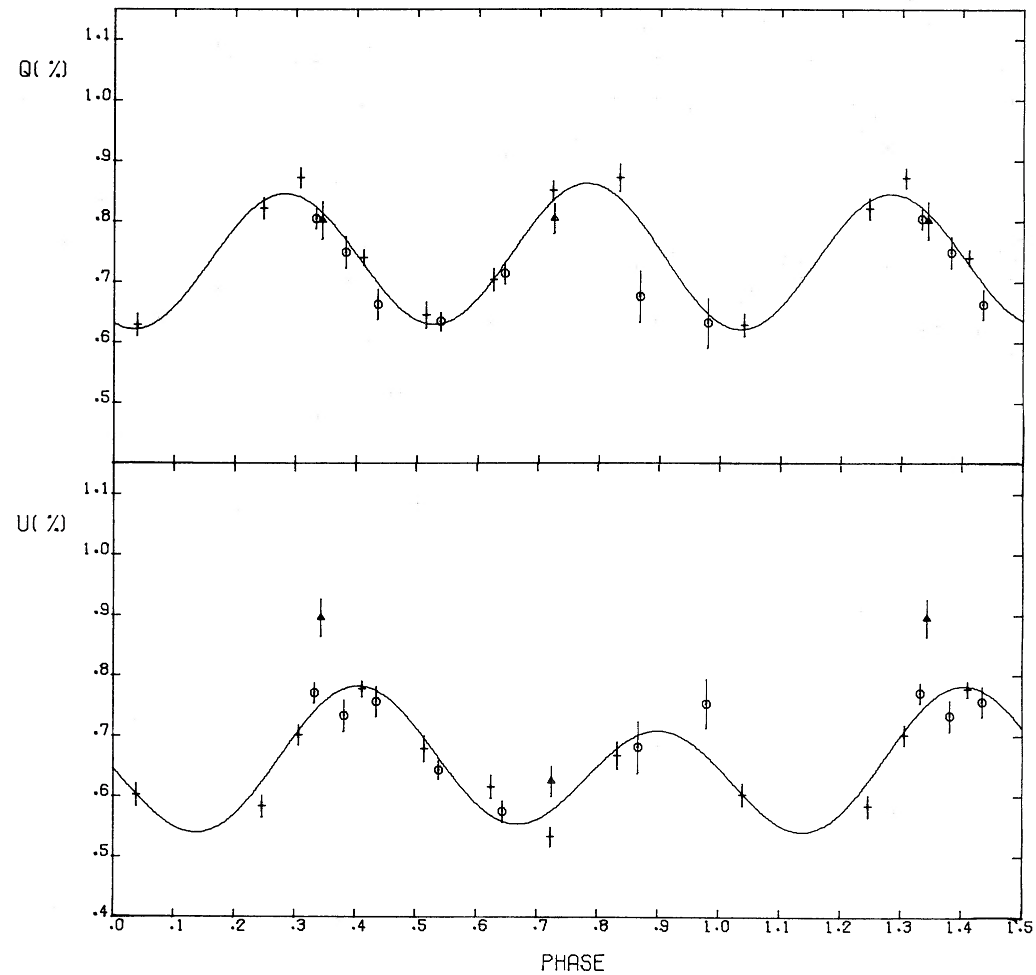

FIG. 1.—Stokes parameters Q and U plotted versus orbital phase for HD 186943. The solid curve is the best fit to a Fourier series up to second harmonic terms. Error bars here and throughout the figures are 2 σ estimates. Observing periods 1, 2, 3, and 4 (see Tables 1 and 4) are denoted here and in Figs 3, 6, 7, and 8 by circles, triangles, crosses, and squares, respectively.

harmonics, for which the coefficients are given in Table 5. The mean deviations from the curve ($\sigma_Q(O-C) = 0.077\%$ and $\sigma_U(O-C) = 0.044\%$) are significantly higher than the instrumental dispersion ($\sigma_{\rm inst} = 0.019\%$). This suggests the presence of supplementary random variations, which are most likely intrinsic to the electron-rich wind of the Wolf-Rayet star as opposed to the O + O subsystem. Figure 4 shows the characteristic locus in the Q-U plane.

Table 6 presents the different parameters of the system as calculated with the polarization model of binary stars. The inclination that results is high: $i = 78\overset{\circ}{.}2 \pm 1\overset{\circ}{.}0$. This is compatible with HD 211853 being an eclipsing system, hence the designation GP Cep for this star. Unfortunately, definitive values of $M \sin^3 i$ are not available because of the perturbation of the absorption lines in the spectrum by the other binary system ($O_2 + O_3$). We will hence adopt the best tentative estimates given by Massey (1981, see his Table 6, with $\Delta m = -0.1$):

$$M(\text{W-R}) \sin^3 i \approx 13{:}M_\odot ,$$

$$M(\text{O}) \sin^3 i \approx 24{:}M_\odot .$$

Using the above inclination value, we find

$$M(\text{W-R}) \approx 14{:}M_\odot ,$$

$$M(\text{O}) \approx 26{:}M_\odot .$$

Since Massey (1981) was not able to supply uncertainties for the values of $M \sin^3 i$, we do not calculate errors for the masses.

The value of the ratio A in Table 6 for HD 211853 is high, but lower than that for HD 186943, implying that the electrons may be less symmetric about, and less concentrated near, the

TABLE 2

HARMONIC COEFFICIENTS OF HD 186943 = WR 127

q_0	u_0	q_1	u_1	q_2	u_2	q_3	u_3	q_4	u_4
+0.7391 ±0.0060	+0.8460 ±0.0080	−0.0023 ±0.0088	−0.0342 ±0.0088	−0.0094 ±0.0086	+0.0158 ±0.0086	−0.1060 ±0.0071	+0.0337 ±0.0071	−0.0431 ±0.0088	−0.0923 ±0.0088

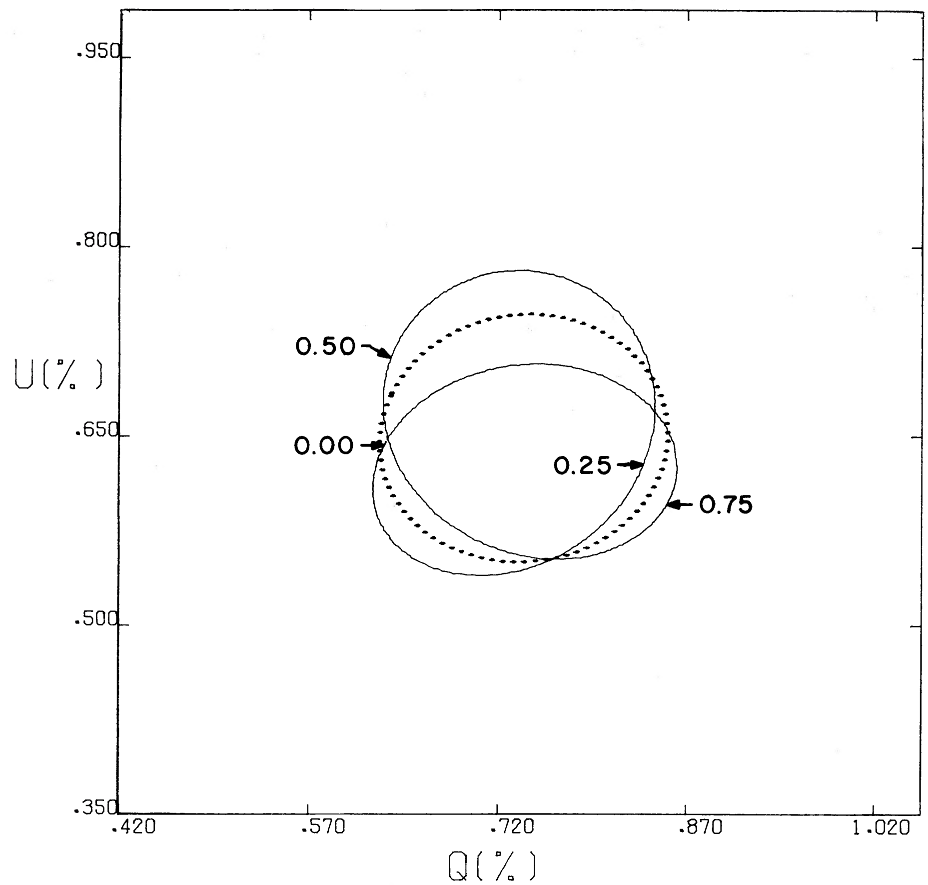

FIG. 2.—Polarimetric variations of HD 186943 in the Q-U plane. The solid curve represents the fitted curve of Fig. 1 and the dotted curve is the (Q_+, U_+) locus, which represents only second harmonic terms. Phases are indicated along the locus.

orbital plane in HD 211853. The direction of concentration of the asymmetric electron scatterers in the orbital plane is given by $\lambda_2 = -7^\circ.0$ or $83^\circ.0 \pm 1^\circ.1$. The former value is fairly close to the direction of the line joining the two stars, compatible with the scattering electrons being associated with the W-R star.

TABLE 3

PARAMETERS CALCULATED WITH THE POLARIZATION MODEL OF BINARY STARS FOR HD 186943 = WR 127

Parameter	Value
i	$55^\circ.7 \pm 8^\circ.2$[a]
Ω	$6^\circ.6 \pm 19^\circ.4$
$W = \tau_0 \gamma_1$	0.4×10^{-4}
$X = \tau_0 \gamma_2$	0.2×10^{-4}
$Y = \tau_0 \gamma_3$	7.7×10^{-4}
$Z = \tau_0 \gamma_4$	-4.1×10^{-4}
$A = \dfrac{\gamma_3^2 + \gamma_4^2}{\gamma_1^2 + \gamma_2^2}$	19.5
$\tan 2\lambda_2 = \dfrac{\gamma_4}{\gamma_3}$......	-0.5 ± 0.5
$\tan \lambda_1 \doteq \dfrac{\gamma^2}{\gamma^1}$	0.5

[a] The error estimated using the work of Aspin, Simmons, and Brown 1981 would make any determination of i futile with the present data.

HD 211853 is the only star among the present five for which the polarization map of neighboring stars along the line of sight shows good, systematic alignment (see Fig. 5). Hence, we attempt to use these stars to define a reliable estimate for the component of interstellar polarization (P_I, Θ_I) for HD 211853, following the procedure outlined in Paper I. The stars were chosen within 2° of HD 211853 on the sky, and to have distance moduli within ± 1 mag of the distance modulus of HD 211853 (12.80). For $n = 24$ such stars, we find a mean ratio $P/E_{B-V} = 4.94\% \pm 0.26$ $(\sigma\sqrt{n})\%$. With $E_{B-V}(\text{W-R}) = 0.79$, this leads to $P_I = E_{B-V}(\text{W-R})\ (P/E_{B-V}) = 3.91\% \pm 0.20\%$. For these same 24 stars, mean values of Q and U lead to a mean $\Theta_I = 49^\circ.5 \pm 1^\circ.1$ $(\sigma\sqrt{n})$ in the equatorial system, reducing to $\Theta_{I,\text{W-R}} = \Theta_I - \Omega/2 = 54^\circ.0 \pm 1^\circ.1$ in the W-R system plane of polarization symmetry. This yields, finally, the estimates

$$Q_{I,\text{WR}} = P_I \cos 2\Theta_{I,\text{WR}} = -1.21\% \pm 0.20\% ,$$
$$U_{I,\text{WR}} = P_I \sin 2\Theta_{I,\text{WR}} = 3.72\% \pm 0.20\% .$$

Now, the center of the (Q_+, U_+) locus in Figure 4 (q_0 and u_0 in Table 5) can be expressed in the W-R system plane of symmetry as

$$Q_c = -0.481\% \pm 0.003\% ,$$
$$U_c = 4.071\% \pm 0.003\% ,$$

TABLE 4

LINEAR POLARIZATION DATA FOR HD 211853 = WR 153

Julian Date (2,440,000+)	P (%)	σ_p (%)	θ	σ_θ	Q (%)	U (%)	ϕ	Observations[a]
5980.803	4.027	0.013	43°6	1°0	0.197	4.022	0.456	1
5981.765	4.098	0.010	43.6	1.0	0.200	4.093	0.600	1
5982.792	4.111	0.014	45.2	1.0	−0.029	4.111	0.753	1
5983.779	4.038	0.028	44.9	1.0	0.014	4.038	0.901	1
6362.600	4.057	0.016	42.4	1.0	0.368	4.040	0.540	3
6363.608	4.181	0.015	44.3	1.0	0.102	4.180	0.690	3
6363.798	4.127	0.012	44.6	1.0	0.058	4.127	0.719	3
6363.924	4.124	0.020	45.3	1.0	−0.043	4.124	0.737	3
6364.576	4.071	0.011	44.5	1.0	0.071	4.070	0.835	3
6364.805	4.014	0.015	44.2	1.0	0.112	4.012	0.869	3
6364.909	4.141	0.038	45.2	1.0	−0.029	4.141	0.885	3
6365.695	4.098	0.012	42.6	1.0	0.343	4.084	0.002	3
6365.836	4.098	0.017	42.9	1.0	0.300	4.087	0.023	3
6366.622	4.151	0.013	43.3	1.0	0.246	4.144	0.141	3
6366.801	4.169	0.026	44.0	1.0	0.145	4.166	0.168	3
6367.674	4.087	0.023	44.4	1.0	0.086	4.086	0.298	3
6367.850	4.078	0.013	44.8	1.0	0.028	4.078	0.324	3
6368.878	4.127	0.015	43.2	1.0	0.259	4.119	0.478	3
6369.834	4.187	0.020	43.3	1.0	0.248	4.180	0.621	3
6371.678	4.028	0.011	43.2	1.0	0.253	4.020	0.897	3
6371.792	4.040	0.010	43.6	1.0	0.197	4.035	0.914	3
6708.793	4.126	0.023	45.2	1.0	−0.029	4.126	0.300	4
6712.912	3.967	0.023	44.6	1.0	0.055	3.967	0.916	4
6718.845	4.083	0.040	45.2	1.0	−0.029	4.083	0.803	4
6721.814	4.261	0.023	45.6	1.0	−0.089	4.260	0.247	4
6723.810	4.086	0.020	43.5	1.0	0.214	4.080	0.545	4
6728.779	4.099	0.020	45.7	1.0	−0.100	4.098	0.288	4
6731.814	4.181	0.022	45.7	1.0	−0.102	4.180	0.742	4
6733.793	4.107	0.018	43.5	1.0	0.215	4.101	0.038	4
6734.746	4.227	0.019	44.7	1.0	0.044	4.227	0.180	4
6735.758	4.066	0.020	45.1	1.0	−0.014	4.066	0.283	4

[a] (1) and (3) as in Table 1; (4) 1986 September 29–November 1 at Mount Lemmon (102 cm).

after derotating q_0, u_0 by Ω. This yields the differences

$$\Delta Q = Q_c - Q_{I,\mathrm{WR}} = +0.73\% \pm 0.20\% ,$$

$$\Delta U = U_c - U_{I,\mathrm{WR}} = +0.36\% \pm 0.20\% .$$

Theoretically, the model of BME predicts $\Delta U = 0$ and $\Delta Q = \tau_0(1-3\gamma_0)\sin^2 i$, where τ_0 is the effective total opacity and τ_0 is a shape factor. While the *observed* values of ΔQ, ΔU are not very restrictive, they are compatible with the theory at the $\sim 2\ \sigma$ level; Robert *et al.* (1988*a*) estimate $\tau_0(1-3\ \gamma_0)\ \sin^3 i \approx 0.2\%$ from detailed calculations of the well-observed eclipsing binary W-R system V444 Cygni, which is expected to have roughly similar properties as the W-R system in HD 211853 = GP Cep.

b) Single-Line Binaries

As in the case of HD 186943 above, there are too few stars around the three systems that follow to be able to place useful constraints on the component of interstellar polarization. Thus, we do not present or discuss polarization maps here.

i) *HD 177230 = WR 123* (WN8)

This star was first claimed to be a binary by Wilson (1948). Much later, Massey and Conti (1980) concluded that the large scatter in the radial velocities (RV) of He II λ4686, observed by Wilson and confirmed by them, did not represent binary modulation. Lamontagne, Moffat, and Seggewiss (1983), combining the Massey/Conti data with their own for He II λ4686 and taking 10 other lines (He II, N III, N IV) of their own data, found a low-amplitude ($K \approx 20$ km s^{-1}) modulation with a period of $P = 1.7616 \pm 0.0002$ days, claimed to be caused by a low-mass companion. Since HD 177230 is a runaway, they expected this companion to be a neutron star that originated from a supernova explosion. However, alternative explanations, such as rotating spots on a single star, cannot be excluded to explain the periodicity.

TABLE 5

HARMONIC COEFFICIENTS OF HD 211853 = WR 153.

q_0	u_0	q_1	u_1	q_2	u_2	q_3	u_3	q_4	u_4
+0.1478	+4.0969	+0.0241	+0.0069	−0.0060	+0.0147	+0.1491	−0.0384	+0.0465	+0.0536
±0.0030	±0.0030	±0.0043	±0.0043	±0.0042	±0.0042	±0.0040	±0.0040	±0.0043	±0.0043

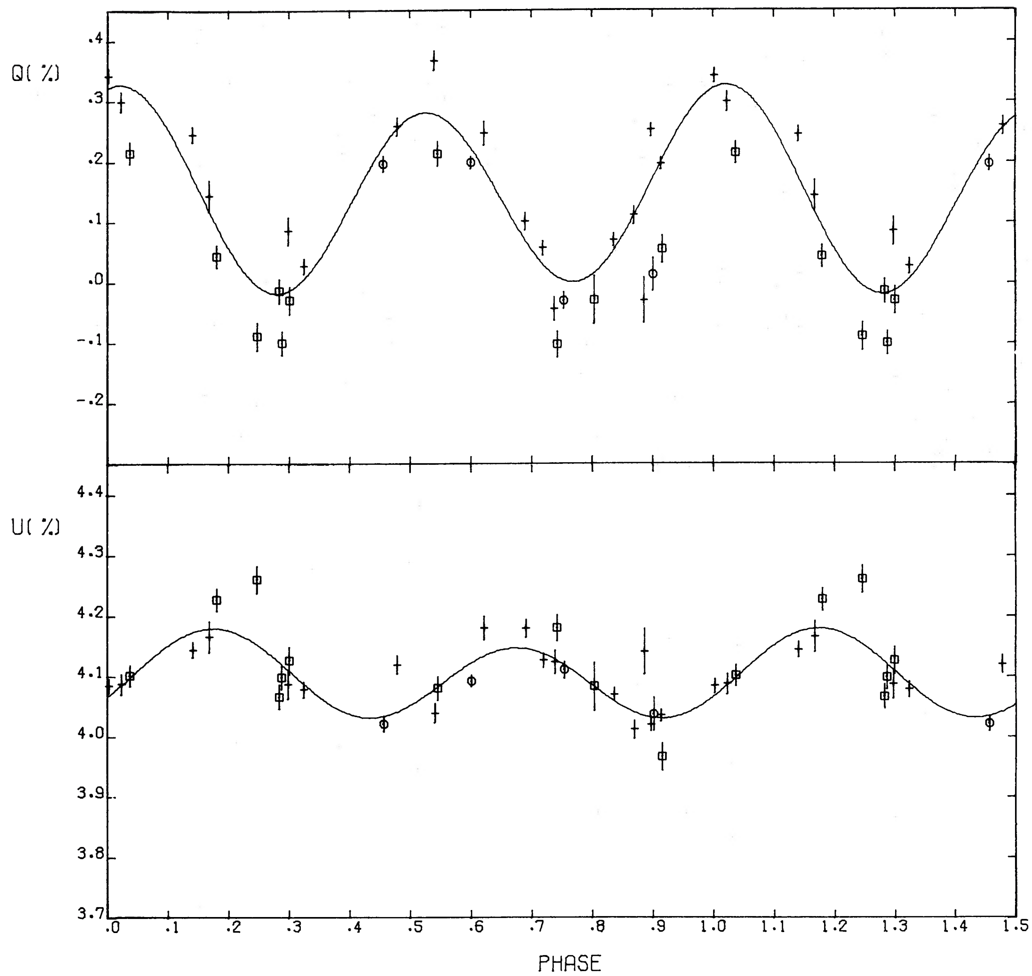

FIG. 3.—Stokes parameters Q and U plotted vs. orbital phase for HD 211853. The solid curve is the best fit to a Fourier series up to second harmonic terms.

TABLE 6

PARAMETERS CALCULATED WITH THE POLARIZATION MODEL OF BINARY STARS FOR HD 211853

Parameter	Value
i	78°2 ± 1°0[a]
Ω	8°9 ± 1°9
$W = \tau_0 \gamma_1$	1.9×10^{-4}
$X = \tau_0 \gamma_2$	1.9×10^{-4}
$Y = \tau_0 \gamma_3$	-14.7×10^{-4}
$Z = \tau_0 \gamma_4$	3.0×10^{-4}
$A = \dfrac{\gamma_3^2 + \gamma_4^2}{\gamma_1^2 + \gamma_2^2}$	5.6
$\tan 2\lambda_2 = \dfrac{\gamma_4}{\gamma_3}$......	-0.25 ± 0.04
$\tan \lambda_1 = \dfrac{\gamma_2}{\gamma_1}$	1.0

[a] The error estimated using the work of Aspin, Simmons, and Brown 1981 would be 5°.

A broad-band B light curve for HD 177230 has been obtained by Moffat and Shara (1986). A period search of the photometric data reveals a period of $P = 2.37$ days with an alias of 1.75 days, which is compatible with the period found by Lamontagne, Moffat, and Seggewiss (1983). The photometric data are thus consistent with the previous data. The light curve also shows large random scatter in addition to the periodic component.

We present in Table 7 and in Figure 6 the polarimetric observations for HD 177230 obtained during two different observing runs. Despite the large variations, no obvious binary modulation is present in the data. A period search yields no significant period. This weakens the case for a binary, but does not necessarily exclude it, since the alleged companion may not be very luminous, and intrinsic random fluctuations in the wind may mask any binary modulation in the polarization.

From the data in Table 7, we find a standard deviation from the simple mean of $\sigma(P) = 0.135\%$. The terminal velocity of the stellar wind for HD 177230 is not directly available. However, the mean value for other known WN8 stars (Abbott and Conti

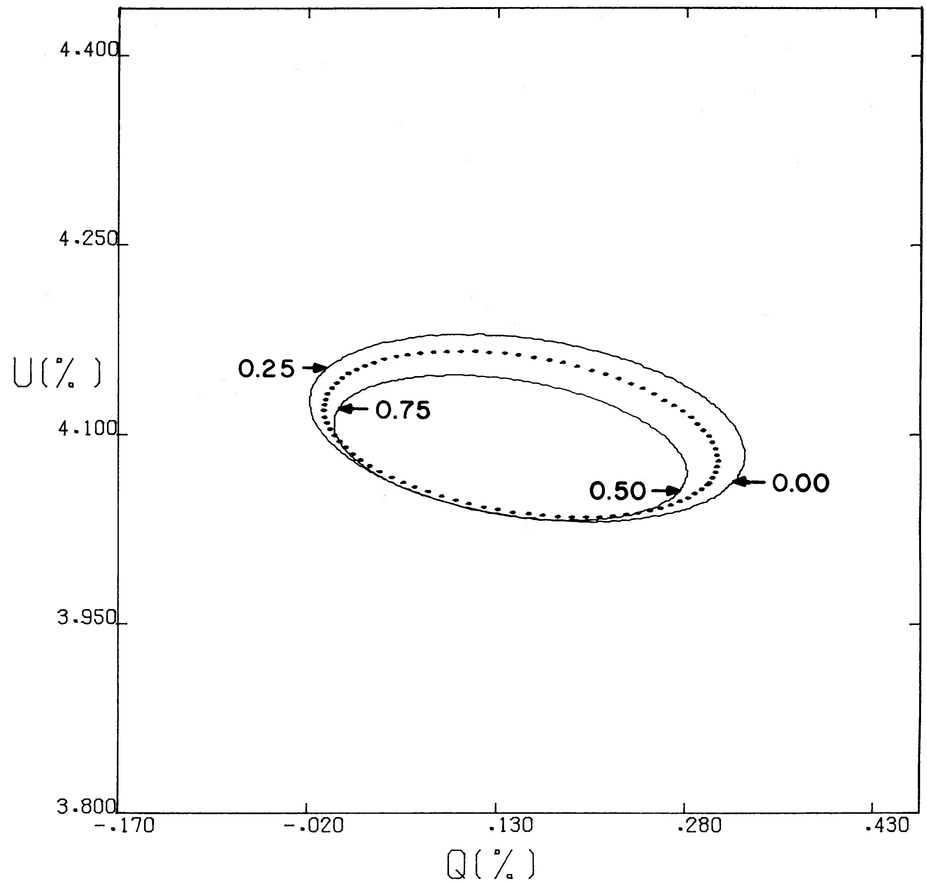

FIG. 4.—Polarimetric variations of HD 211853 in the Q-U plane. The solid curve represents the fitted curve of Fig. 3 and the dotted curve is the (Q_+, U_+) locus. Phases are indicated along the locus.

1987) is relatively low ($v_\infty \approx 1680 \pm 320$ km s^{-1}). The combination of high scatter in polarization and low terminal velocity for HD 177230 is compatible with the correlation presented by Drissen *et al.* (1987, hereafter Paper II) between the standard deviation and the terminal velocity for a sample of W-R stars of different subtypes.

A plot in the Q-U plane gives no valuable information since there are too few data obtained during a long uninterrupted observing run.

ii) *209 BAC = WR 124* (WN8)

This star is also a runaway, with a peculiar radial velocity of ≈ 150 km s^{-1}. It was proposed that it might be a binary similar to HD 177230 by Moffat, Lamontagne, and Seggewiss (1982). These authors found a low-amplitude ($K \approx 13$ km s^{-1}) RV modulation with a period of 2.36 ± 0.2 days. Assuming this to be due to binary modulation, they derived a mass function which indicates a low-mass companion (1.0–1.7 $M_\odot$). They also obtained some photometric data in the B and V bands that show systematic variations with the spectroscopic period. The color $(B-V)$ also shows phase-dependent variations which are interpreted in terms of an occulted object which is redder than the W-R star. Moffat and Shara (1986) later obtained another photometric curve in the B broad band. Their data independently reveal a period of $P = 2.73 \pm 0.2$ days which is compatible with the previous period of Moffat, Lamontagne, and Seggewiss (1982). The light curve also shows significant noise in addition to the periodic component, although the noise is of lower amplitude than for HD 177230.

The polarimetric observations obtained during an 8 day interval are presented in Table 8 and in Figure 7. Only incoherent variations with an amplitude of $\Delta P \approx 0.50\%$ are present in the data. The standard deviation from the simple mean is $\sigma(P) = 0.122\%$. As for HD 177230, of similar spectral subtype, this result is compatible with the correlation of Paper II between polarization scatter and terminal velocity. Note the relatively large variation in both P and Θ at JD $\sim$ 2,446,218 on a time scale of $\sim$4 hr; this may be the result of a large blob ejected in the wind in a curved trajectory.

A plot of Q versus U (not presented here) shows only stochastic variations similar to the case of the WN8 star HD 96548 (= WR 40) presented in Paper II, revealing a random character. This suggests a lack of a preferred axis or plane for this variation.

iii) *HD 187282 = WR 128* (WN4)

Antokhin, Aslanov, and Cherepashchuk (1982) claimed that HD 187282 was a WN4 + NS (neutron star) binary with a 3.85 ± 0.15 day period. Spectrosocopic data obtained by Lamontagne (1983) revealed a possible period of $P = 3.56$ days

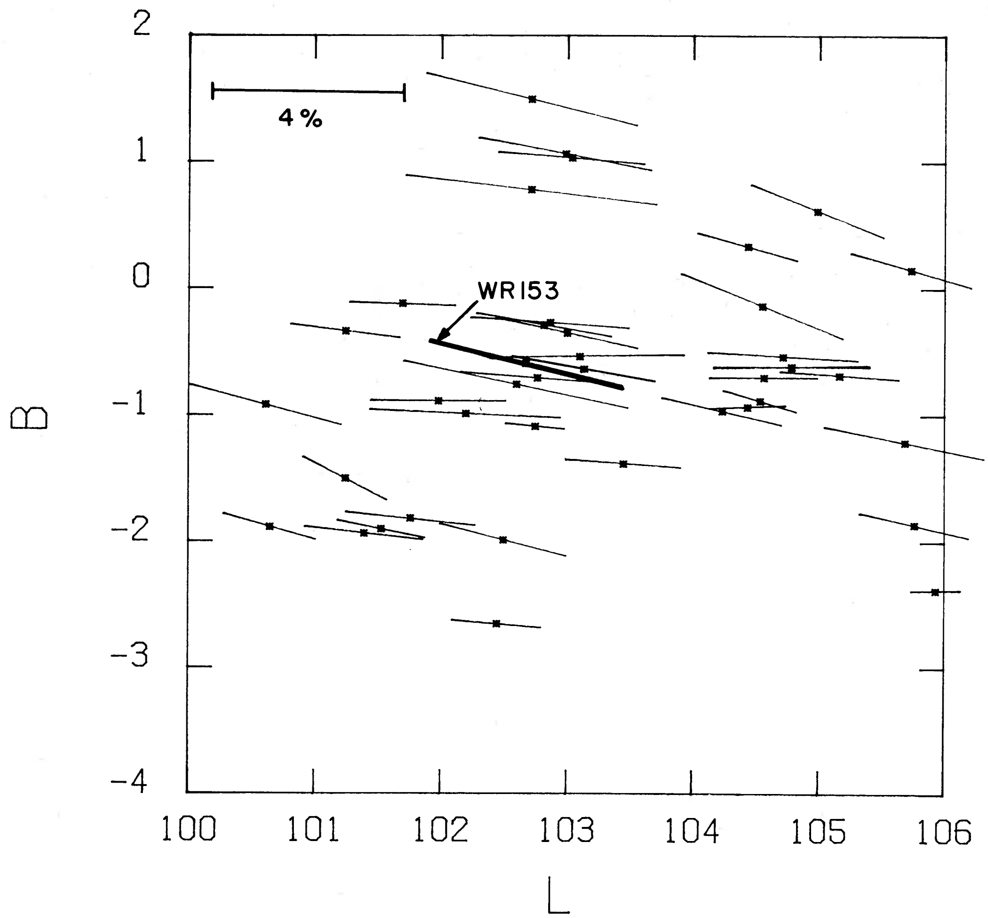

FIG. 5.—Polarization map for stars in a 6° × 6° region around HD 211853 and within 1 mag in true distance modulus. The length of the vectors is proportional to P(%) with the scale indicated in the upper left. The W-R star itself is identified by a thicker bar in the center of the field; we show the center of the (Q_+, U_+) locus transformed to Galactic coordinates.

TABLE 7

LINEAR POLARIZATION DATA FOR HD 177230 = WR 123

Julian Date (2,440,000+)	P (%)	σ_p (%)	θ	σ_θ	Q (%)	U (%)	Observations[a]
6213.830.......	1.656	0.026	78°9	0°5	−1.533	0.626	2
6213.940.......	1.644	0.033	80.6	0.6	−1.556	0.530	2
6214.950.......	1.557	0.066	82.8	1.2	−1.508	0.387	2
6217.810.......	1.557	0.026	77.9	0.5	−1.420	0.638	2
6217.920.......	1.668	0.027	79.7	0.5	−1.561	0.587	2
6218.790.......	1.739	0.033	81.6	0.5	−1.665	0.503	2
6218.900.......	1.380	0.029	80.8	0.6	−1.309	0.436	2
6219.830.......	1.535	0.023	75.8	0.4	−1.350	0.730	2
6219.880.......	1.433	0.026	76.3	0.5	−1.272	0.659	2
6220.930.......	1.759	0.029	84.1	0.5	−1.722	0.360	2
6221.830.......	1.485	0.061	78.1	1.2	−1.359	0.599	2
6221.860.......	1.515	0.050	79.4	0.9	−1.412	0.548	2
6221.940.......	1.721	0.034	82.1	0.6	−1.656	0.469	2
6362.640.......	1.598	0.035	77.0	0.6	−1.436	0.701	3
6363.640.......	1.731	0.039	83.4	0.6	−1.685	0.395	3
6364.640.......	1.478	0.075	83.0	1.4	−1.434	0.358	3
6365.650.......	1.742	0.071	77.2	1.2	−1.571	0.753	3
6366.600.......	1.678	0.026	81.6	0.4	−1.606	0.485	3
6367.660.......	1.707	0.096	81.0	1.6	−1.623	0.527	3
6371.620.......	1.711	0.032	83.4	0.5	−1.666	0.391	3

[a] See Table 1.

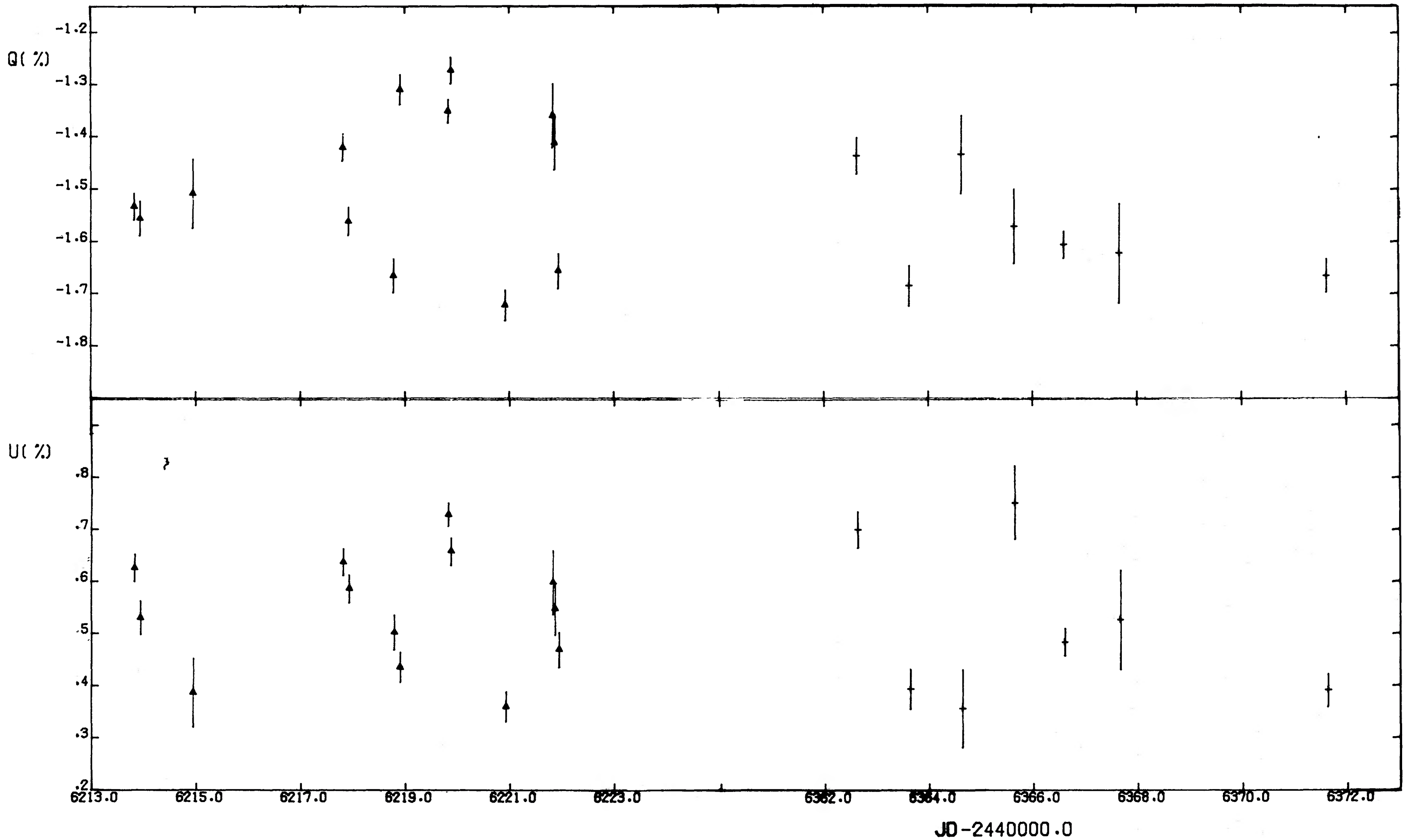

FIG. 6.—Stokes parameters Q and U plotted as a function of Julian date for HD 177230 = WR 123

TABLE 8

LINEAR POLARIZATION DATA FOR 209 BAC = WR 124

Julian Date (2,440,000+)	P (%)	σ_p (%)	θ	σ_θ	Q (%)	U (%)	Observations[a]
6213.750.....	1.972	0.033	42°2	0°5	0.192	1.963	2
6213.860.....	1.940	0.034	41.2	0.5	0.257	1.923	2
6214.730.....	2.043	0.037	45.6	0.5	−0.043	2.043	2
6214.780.....	2.023	0.024	45.5	0.3	−0.035	2.023	2
6214.930.....	2.055	0.026	41.3	0.4	0.265	2.038	2
6217.710.....	2.427	0.056	46.3	0.7	−0.110	2.425	2
6217.760.....	2.233	0.031	44.3	0.4	0.055	2.232	2
6217.870.....	2.066	0.033	40.7	0.5	0.309	2.043	2
6217.950.....	2.147	0.024	42.0	0.3	0.224	2.135	2
6218.750.....	2.052	0.037	40.3	0.5	0.335	2.024	2
6218.930.....	2.070	0.022	42.0	0.3	0.216	2.059	2
6219.760.....	2.063	0.026	40.7	0.4	0.308	2.040	2
6219.920.....	2.018	0.036	41.6	0.5	0.239	2.004	2
6220.890.....	2.176	0.032	39.4	0.4	0.423	2.135	2
6221.750.....	2.045	0.032	42.9	0.5	0.150	2.040	2

[a] See Table 1.

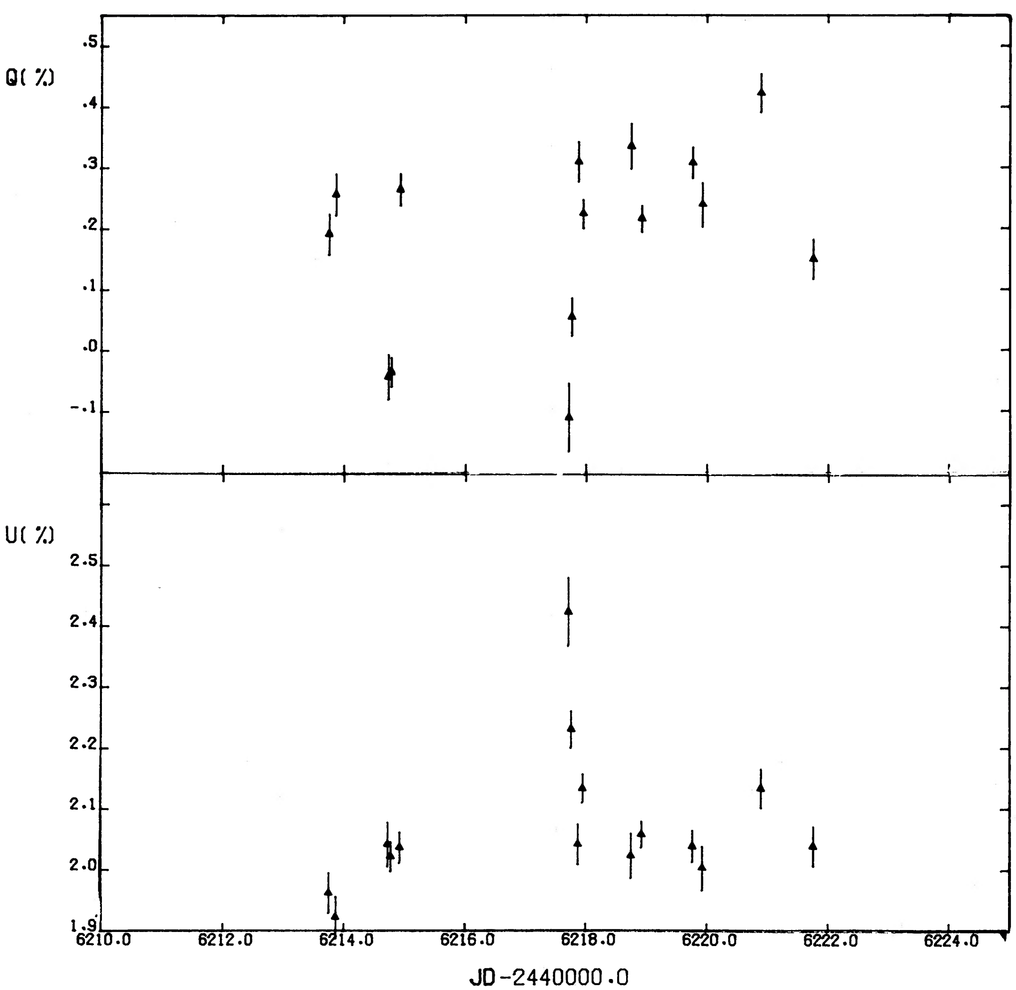

FIG. 7.—Stokes parameters Q and U plotted as a function of Julian date for 209 BAC = WR 124

TABLE 9

LINEAR POLARIZATION DATA FOR HD 187282 = WR 128

Julian Date (2,440,000+)	P (%)	σ_p (%)	θ	σ_θ	Q (%)	U (%)	Observations[a]
5980.750......	1.279	0.024	10°2	0°5	1.199	0.446	1
5981.680......	1.227	0.019	10.2	0.4	1.150	0.428	1
5982.680......	1.212	0.021	8.7	0.5	1.157	0.362	1
5983.680......	1.202	0.020	9.2	0.5	1.141	0.379	1
6217.790......	1.120	0.027	10.0	0.7	1.052	0.383	2
6218.850......	1.240	0.016	12.3	0.4	1.127	0.516	2
6219.730......	1.184	0.027	7.0	0.7	1.149	0.286	2
6221.920......	1.185	0.024	8.2	0.6	1.136	0.339	2

[a] See Table 1.

which is fairly compatible with the previous result. However, a light curve obtained by Moffat and Shara (1986) shows only weak, noisy modulation with phase based on this period.

Our polarimetric observations presented in Table 9 and plotted versus Julian date in Figure 8 show only low-amplitude, incoherent variations ($\Delta P \approx 0.15\%$) However, the data obtained during the two short separate runs are probably too few, and more extensive coverage is required for a more definitive check if these variations are caused by binary modulation. The standard deviation from the simple mean is $\sigma(P) = 0.046\%$, and the terminal velocity of the wind, based on its spectral type, is $v_\infty \approx 2375 \pm 625$ km s^{-1}. Once again, this

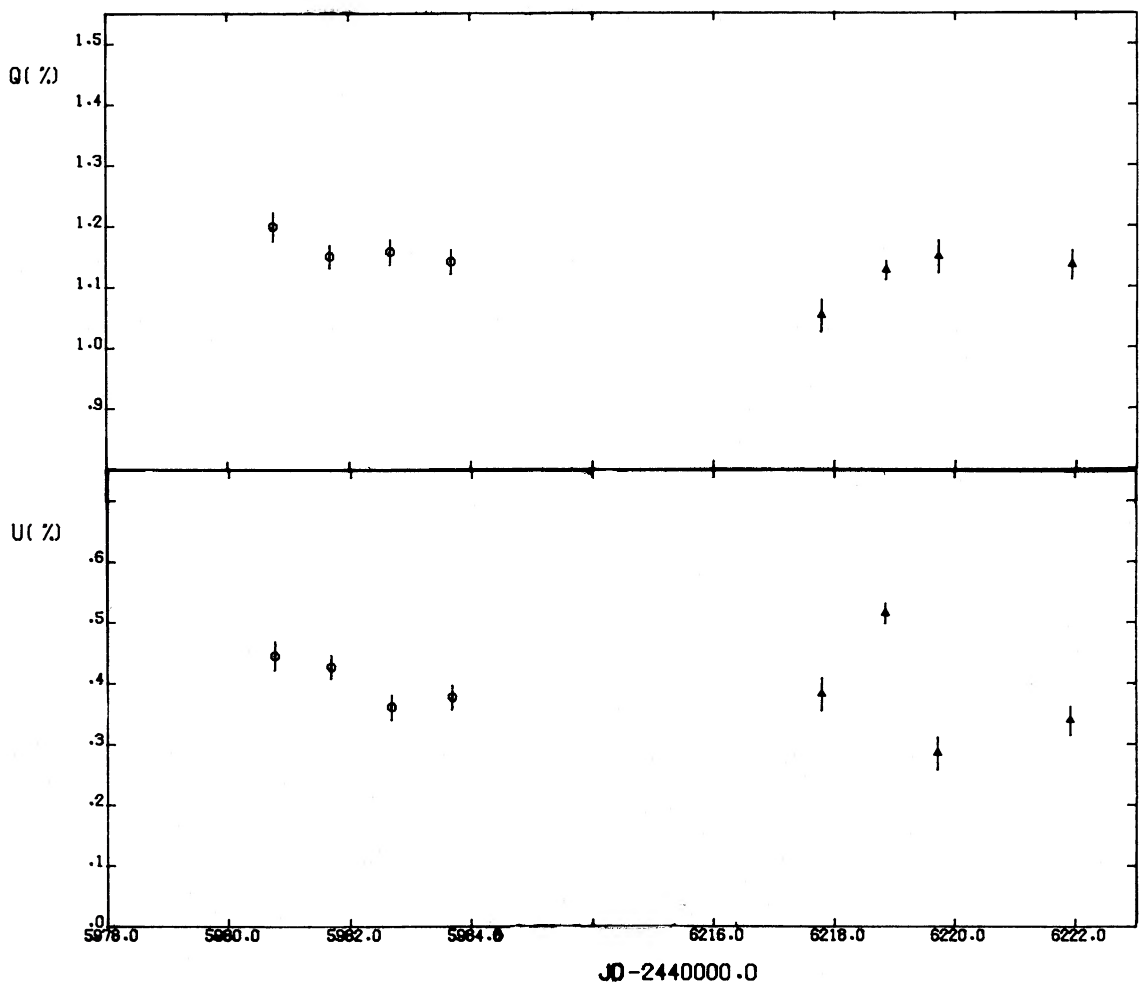

FIG. 8.—Stokes parameters Q and U plotted as a function of Julian date for HD 187282 = WR 128

result fits very well with the $\sigma(P) - v_\infty$ correlation of Paper II. Finally, the small number of observations prevents us from obtaining any useful information from a plot in the Q-U plane.

IV. MASS-LOSS RATES

As noted in § II, the semimajor axis of the second harmonic (Q_+, U_+) locus described by a typical W-R binary system in the Q-U polarization plane can be expressed as a function of several observable parameters (see eq. [3]). Using a simple parameterized wind velocity law, $v(R') = v_\infty(1 - R_*/R')^\beta$ (see Castor and Lamers 1979, with starting velocity $v_0 \approx 0$), where R_* is the stellar radius, and expressing the integral in equation (3) in terms of dimensionless quantities, the semimajor axis of the polarization ellipse in the Q-U plane can be written as

$$A_p = \frac{(1 + \cos^2 i)3\sigma_t f_c \dot{M}}{(16\pi)^2 m_p v_\infty a} I , \quad (4)$$

with

$$I = \int_0^\infty \int_0^\pi \int_0^{2\pi} \frac{\sin^3\theta \cos 2\phi \, d(R/a) d\theta \, d\phi}{(R'/a)^2(1 - R_*/R')^\beta} . \quad (5)$$

Note that $(R'/a)^2 = 1 + (R/a)^2 - 2(R/a) \sin\theta \cos\phi$ and the integration excludes the region interior to $R' = R_*$, as well as the part of the W-R wind not seen by the companion (taken here to be a point source). The mass-loss rate is then given by

$$\dot{M} = \frac{(16\pi)^2 m_p v_\infty a A_p}{(1 + \cos^2 i)3\sigma_t f_c I} \quad (6)$$

or

$$\dot{M}(M_\odot \text{ yr}^{-1}) = \frac{2.33 \times 10^{-7} A_p a(R_\odot) v_\infty(\text{km s}^{-1})}{(1 + \cos^2 i) f_c I} .$$

Along with various measurable quantities (A_p, a, v_∞, i, f_c), the numerical calculation of the integral I yields an estimate for the mass-loss rate. In order to evaluate this integral, one has to choose a specific wind velocity law (characterized by the parameter β). Castor, Abbott, and Klein (1975), neglecting rotation and the finite size of the star, developed a model which predicted that $\beta = 0.5$ should represent the best fit to the data for O stars. Later, Friend and Abbott (1986) included these effects and came to the conclusion that $\beta = 0.8$ was a better fit to the observations. For W-R stars, the eclipse data of CEK for the WN5 component of V444 Cygni yield an empirical velocity law that can be fairly well fitted by β of the order of unity or slightly less. We also note that for $\beta > 1$, the integral diverges due to problems at $R' = R_*$.

Another problem that has to be confronted is where to start the integration relative to the surface of the W-R star. We characterize this by $\varepsilon = R_i'/R_*$, where R_i' is measured with respect to the center of the W-R star, as noted previously. The polarization model of binary stars assumes that the scattering envelope is optically thin, in which case one would have $\varepsilon = 1.00$ (neglecting the non–point-source nature of the O companion). However, the eclipse observations of the WN5 + O6 binary V444 Cygni at phase 0.5 (W-R star being eclipsed) by CEK show that the radial electron opacity becomes rapidly large ($\tau > 0.2$) within $R' \approx 2R_*$. On this basis, one might expect $\varepsilon \approx 2$ as a good compromise, not only for the W-R star in V444 Cygni, but possibly for all W-R stars. As it turns out, this avoids the problem noted above of divergence of the integral I.

Note that in the unlikely event that the wind is optically thin even at $R' = R_*$, the polarization anywhere at the surface would drop to zero in any case (see Rudy 1978). The eclipse polarization data for V444 Cygni also support a value of $\varepsilon \approx 2$ (Robert *et al.* 1988*a*).

The effects of varying the parameters β and ε for a given value of a/R_*, on the value of the dimensionless integral I, are not immediately obvious. We present in Table 10 several estimates of I, obtained by numerical integration, for three different combinations of β and ε in plausible ranges, as a function of a/R_*. Note that for very large separations, all values of I approach the same limit ($I = 7.75$). This is due to the fact that, for large separations, the electrons very close to the W-R star play only a minor role compared to the exterior parts of the wind (low density but large volume). In Figure 9, one can see that the difference between the two velocity laws mentioned above ($\beta = 0.5$ and $\beta = 0.8$) for a fixed value of ε ($\varepsilon = 1.00$) becomes important (>20%) only for very close systems ($a \lesssim 10R_*$). Consequently, taking $\beta = 0.5$ or 0.8 has only a small effect on I, and we will simply adopt the $\beta = 0.5$ law. For this velocity law, we illustrate in Figure 10 the difference between an envelope that is totally optically thin ($\varepsilon = 1.00$) and an envelope that is optically thick out to $\varepsilon = 2.0$ and thin beyond that. Again the difference in I is small (<20% for a $\gtrsim 10R_*$). We adopt $\varepsilon = 2.0$ as a reasonable approximation in view of the eclipse data for V444 Cygni. Note that a value of ε significantly greater than unity reduces the importance of the precise value for β that one adopts.

We present in Table 11 the different parameters characterizing each system considered in this paper, as well as the estimated mass-loss rates. Note that in order to include systems with elliptical orbits, we have replaced the semimajor orbital axis a by $a(1 - e)$ in equation (6) so that, for the eccentric orbits, the quantity A_p refers to the polarization amplitude near periastron passage. Clearly, the two systems with elliptical orbits will be of lower weight in this context.

We also note that the value of R_* we choose in our calculations has only a small effect on the value of the integral. In

TABLE 10

VALUES OF THE DIMENSIONLESS INTEGRAL I FOR DIFFERENT VALUES OF a/R_*, β, AND ε

a/R_*	$\beta = 0.5$, $\varepsilon = 1.0$	$\beta = 0.8$, $\varepsilon = 1.0$	$\beta = 0.5$, $\varepsilon = 2.0$
2	4.70 ± 0.22	12.84 ± 0.95	...
3	5.83 ± 0.13	12.09 ± 0.12	...
6	7.79 ± 0.15	...	4.25 ± 0.05
10	...	10.76 ± 0.82	5.96 ± 0.08
15	8.16 ± 0.12	...	...
20	...	9.74 ± 0.65	7.15 ± 0.09
30	8.08 ± 0.07	9.21 ± 0.25	7.37 ± 0.07
1725	7.77 ± 0.04	...	7.77 ± 0.04
10000	7.75 ± 0.04	7.75 ± 0.03	7.75 ± 0.04

NOTE.—The integral I is based on equation (5). The uncertainties in I are due to numerical approximation. Other variables are as follows: a is the mean orbital separation, R_* is the radius of the W-R core, β is the index in the velocity law $v(R) = v_\infty (1 - R_*/R')^\beta$, and ε gives the starting point for the integration R_i'/R_*. Some values of I have not been calculated because either the trend was already clear or the computing time became excessive.

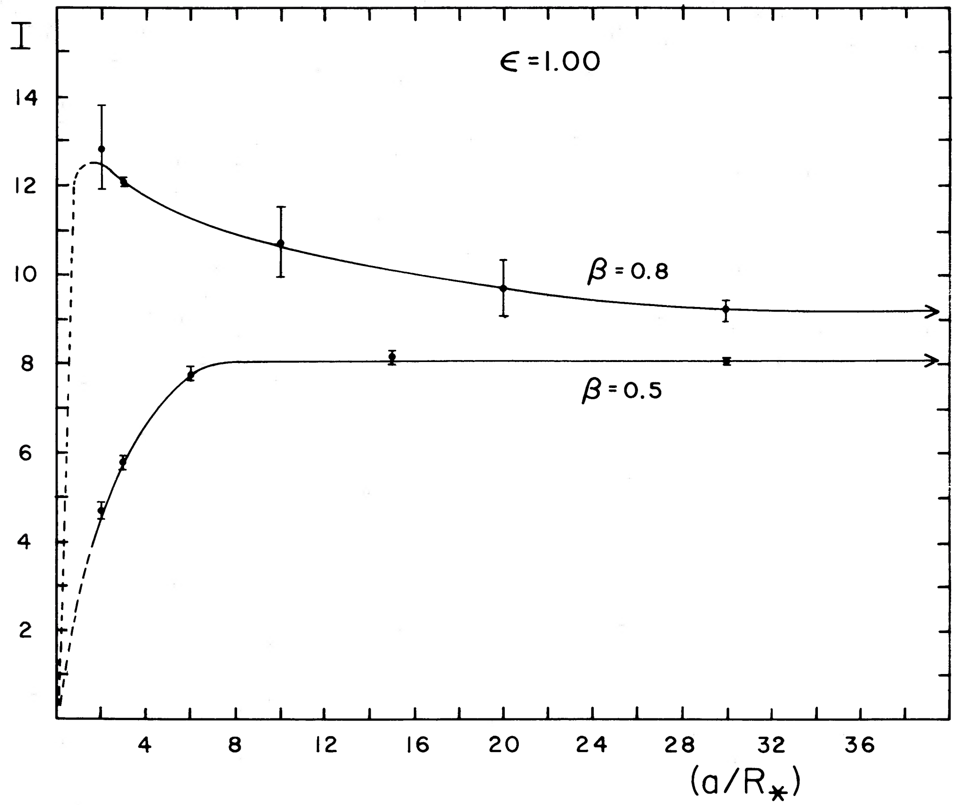

FIG. 9—Variation of the computed integral I (see eq. [4]) as a function of the ratio of the orbital separation to the W-R stellar radius (a/R_*) for two different velocity laws ($\beta = 0.5$, $\beta = 0.8$) and a fixed value of $\varepsilon = R'(\min)/R_* = 1.00$.

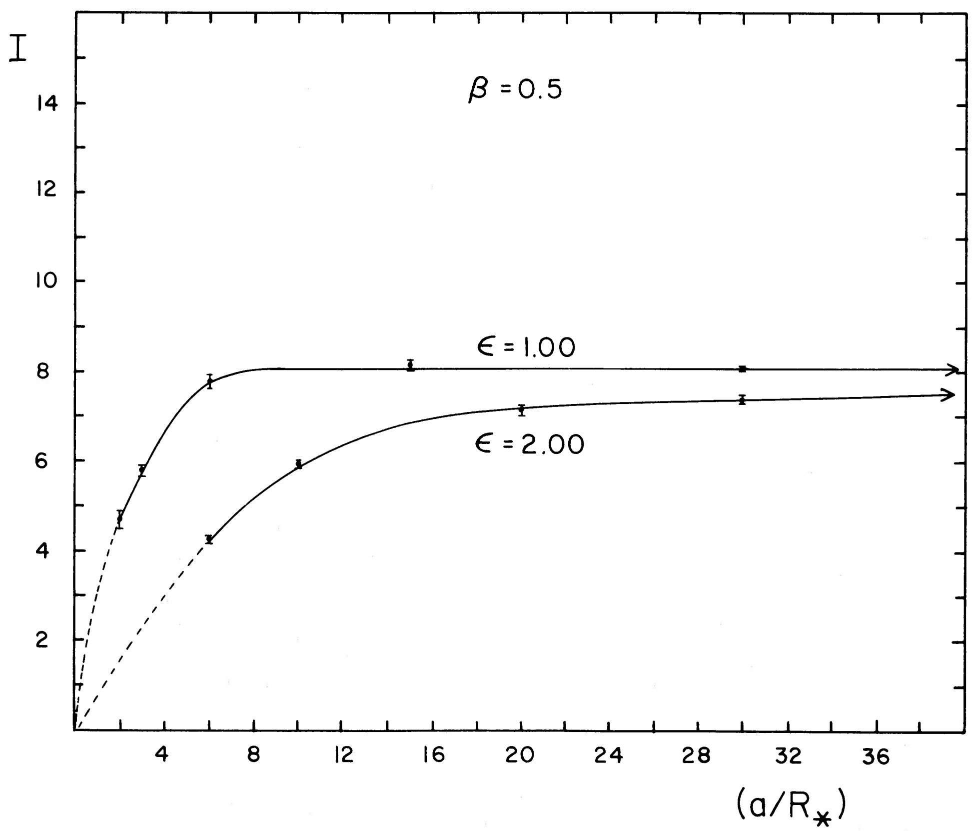

FIG. 10.—Variation of the computed integral I as a function of (a/R_*) for two different vaues of ε ($\varepsilon = 1.00$, $\varepsilon = 2.00$) and a fixed velocity law ($\beta = 0.5$)

TABLE 11

PARAMETERS FOR KNOWN MASSIVE W-R BINARIES

Star	Spectral Type	M_v	f_c	v_∞ (km s^{-1})	R_*(WR) ($R_\odot$)	$a \sin i$ ($R_\odot$)	a ($R_\odot$)	e	i	A_p	I	$M \sin^3 i$ ($M_\odot$)	M ($M_\odot$)	$\log \dot{M}$ (WR) ($M_\odot$ yr^{-1})
HD 68273 (WR 11) ...	WC8 O9I	−4.9 −6.5	0.81 ± 0.10	2000 ± 200[a]	5:[b]	285 ± 9[c]	303	0.40[c]	70°: ± 10°:	0.0010[d]	7.5	18[c] 33[c]	21 39	−4.90:
HD 97152 (WR 42) ...	WC7 O5–7	−4.9 −5.5	0.63 ± 0.15	2800 ± 300[e]	5:[b]	36 ± 1[f]	52	0[f]	43.5 ± 3.0[d]	0.0019[d]	6.0	3.6[f] 6.1[f]	11 19	−4.95
HDE 311884 (WR 47)	WN6 O5:	−5.2 −5.7	0.61 ± 0.15	3320 ± 910[g]	7:[b]	64 ± 2[h]	66	0[h]	76.9 ± 1.7[i]	0.0032[i]	5.7	40[h] 48[h]	41 49	−4.35
HD 152270 (WR 79) ..	WC7 O5–8	−4.9 −5.35	0.60 ± 0.16	3200 ± 200[e]	5:[b]	34 ± 1:[j]	48	0[j]	44.8 ± 3.0[d]	0.0027[d]	5.7	1.8[j] 5.0[j]	5.1 14	−4.71
HD 186943 (WR 127) .	WN4 O9.5	−3.9 −4.25	0.58 ± 0.16	2375 ± 625[g]	3:[b]	55 ± 2[k]	67	0[k]	55.7 ± 8.2[l]	0.0012[l]	7.2	9.3[k] 20[k]	16 35	−5.09
HD 190918 (WR 133) .	WN4.5 O9.5Ia	−3.9 −6.85	0.94 ± 0.04	1750 ± 100[m]	3:[b]	88 ± 9[n]	340	0.48[n]	15: ± ?[n]	0.0010:[o]	7.5	0.22[n] 0.51[n]	13 29	−5.28:
HD 193576 (WR 139) .	WN5 O6	−4.7 −5.5	0.68 ± 0.14	2500 ± 100[p]	3[p]	35 ± 1[q,r]	36	0[q,r]	78.8 ± 0.5[o]	0.0019[o]	6.4	9.3[q,r] 23[q,r]	9.8 24	−5.05
HD 197406 (WR 148) .	WN7 ...	−6.5 −6.5:	0.50: ± 0.16	2350 ± 650[g]	11:[b]	38 ± 4:[s]	41	0[s]	66.6 ± 4.0[s]	0.0024[s]	2.8:	31[s] 7.4[s]	40 9.6	−4.48:
HD 211853 (WR 153) .	WN6 O_1	−5.2 −4.5	0.34 ± 0.15	2410 ± 910[g]	7:[b]	50 ± 3:[k]	51	0[k]	78.2 ± 1.0[l]	0.0016 × 1.7[l]	4.9	13[k] 24[k]	14 26	−4.35:
HD 214419 (WR 155) .	WN7 O	−6.5 −5.5	0.28 ± 0.13	2350 ± 650[g]	11[t]	24 ± 1:[t]	25	0[t]	78.0 ± 1.0[u]	0.0038[u]	1.8:	37[t] 28[t]	40 30	−4.00:

NOTES.—Identification number and spectral types of W-R stars from van der Hucht *et al.* 1981. M_v of W-R stars from the M_v-Sp calibration of Lundström and Stenholm (1984); M_v of O companions from the M_v-Sp calibration of Schmidt-Kaler (1982). Luminosity class V assumed for O stars unless indicated otherwise (Iab assumed for WR 11). For the single-line binary WR 148 we assume M_v(companion) ≈ M_v(W-R), following Drissen *et al.* (1986*a*), and $M_{\text{W-R}} = 40\ M_\odot$. Spectral types of O9V for all three O stars in WR 153 and O6V for the O companion in WR 155 are assumed. If M_v(W-R) in WR 47 were even brighter (see Seggewiss 1974), this would make $\dot{M}$ (WR 47) even higher. Errors in $f_c = (1 + 10^{-0.4\Delta M_v})^{-1}$, where $\Delta M_v = M_v(\text{W-R}) - M_v(\text{O})$, are based on error propagation with $\sigma_{M_v} = 0.5$ for all individual stars (see the above references for M_v). Error estimates for i are based on formal errors of the parameters independently fitted to the polarization data, except for WR 133 whose value of i comes from an assumed mass for its O component, based on its spectral type, along with the orbital value of $M(\text{O}) \sin^3 i$. A_p for WR 153 has been corrected for dilution by the assumed unpolarized light from $O_2 + O_3$. The integral I was calculated with $\beta = 0.5$, $\varepsilon = 2$.

[a] Barlow, Smith, and Willis 1981.
[b] Rublev 1975.
[c] Moffat *et al.* 1986.
[d] St.-Louis *et al.* 1987.
[e] Torres, Conti, and Massey 1986.
[f] Davis, Moffat, and Niemela 1981.
[g] Abbott and Conti 1987.
[h] Niemela, Conti, and Massey 1980.
[i] Robert *et al.* 1988*a*.
[j] Seggewiss 1974.
[k] Massey 1981.
[l] This work.
[m] Abbott *et al.* 1986.
[n] Fraquelli, Bolton, and Horn 1987.
[o] Robert *et al.* (1988*b*).
[p] Cherepashchuk, Eaton, and Khaliullin 1984.
[q] Münch 1950.
[r] Ganesh, Bappu, and Natarajan 1967.
[s] Drissen *et al.* 1986*a*.
[t] Leung, Moffat, and Seggewiss 1983.
[u] Drissen *et al.* 1986*b*.

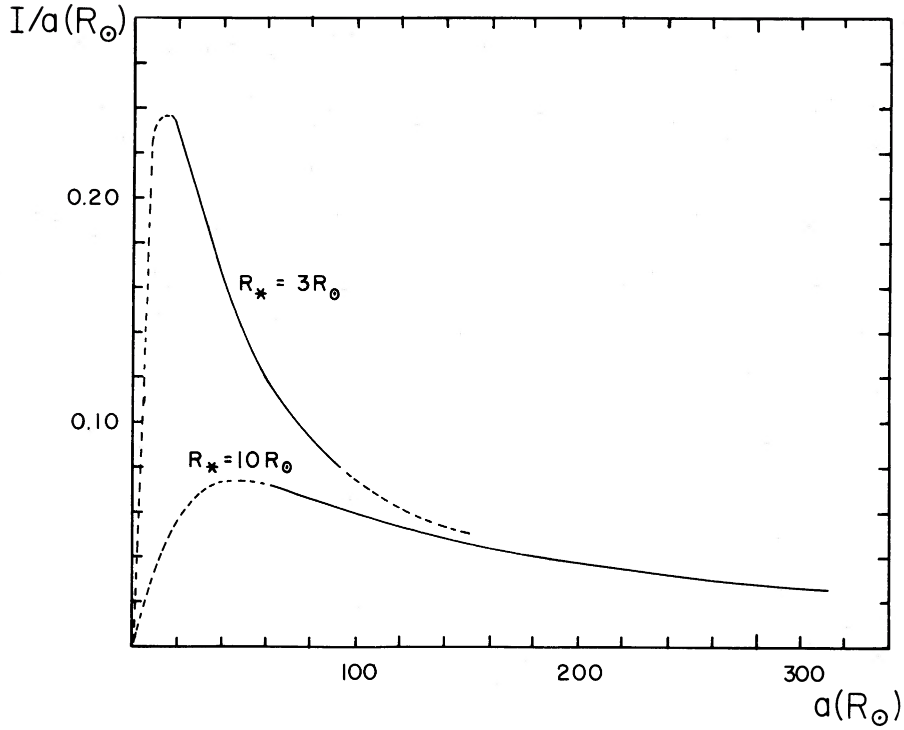

FIG. 11.—The orbital part of the mass-loss rate estimate, I/a, from eq. (5), vs. orbital separation a, for two extreme values of the W-R core radius R_*

Figure 11 we show a plot if I/a versus a for two stellar radii (3 $R_\odot$ and 10 $R_\odot$), which represent the typical range believed to prevail for W-R stars. One can clearly see that, everything else being equal, the difference in the estimated mass-loss rates for different radii becomes important (> 20%) only for moderately close systems ($a < 80\ R_\odot$). Thus, even if the value of the stellar radius (which is a parameter very difficult to establish for W-R stars because of the thick wind near the stellar surface) is relatively imprecise, it does not generate considerable error for most systems. In any case, we can take different values of R_* into account, insofar as the W-R subclass indicates this (see Rublev 1975).

The uncertainty in the estimate of $\dot{M}$ can be derived from the propagation of the errors of the independent factors. In equation (6), we estimate approximate, typical errors (*a*) of A_p to be ± 0.0002 (10%), (*b*) of $a \sin i$, the spectroscopically observed quantity, to be $\pm 5\%$, (*c*) of v_∞ to be $\pm 20\%$, (*d*) of $(\sin i)(1 + \cos^2 i)$ to be $\pm 5\%$ in the worst case, assuming $\sigma_i \approx 5°$, (*e*) of f_c to be $\pm 25\%$, and (*f*) of I to be $\pm 20\%$, based on probable ranges of β and ε. These lead to a typical formal random error in $\dot{M}$ of $\sigma_{\dot{M}} \approx 40\%$, not too different from the typical errors of $\dot{M}$ from radio data (Abbott *et al.* 1986): $\sigma_{\rm rms}(\log \dot{M}) \approx 0.25$, i.e., $\dot{M}^{+78\%}_{-44\%}$. Systematic errors are difficult to estimate, e.g., if He is not completely He^{++} as assumed or if the wind is strongly distorted by the companion.

The uncertainty in the mass of the W-R component depends on the independent errors in the spectroscopically determined values of M(W-R) $\sin^3 i$ and of $\sin^3 i$. For the former, we estimate approximate typical errors of $\pm 10\%$, and maximum errors for the latter of $\pm 28\%$ (assuming $\sigma_i \approx 5°$ and $i = 44°$, close to the lowest inclination determined from polarization in Table 11). This leads to maximum formal random errors in M(W-R) of $\sim 30\%$; a good example where this applies is HD 186943 (see § III*a*[*i*]).

We note that the orbital inclinations in Table 11 correspond well with the distribution expected for a random sample. For example, one expects to find as many systems with $i > 60°$ as with $i < 60°$; one has $n = 6$ and $n = 4$, respectively. Hence, a potential bias toward larger i for noisy data (see ASB) is not evident here. If anything, there may be a slight selection effect preventing the spectroscopic detection of orbits for very low i systems.

In Figure 12, we present the mass-loss rates estimated in this paper as a function of the mass of the W-R star. We now have a reliable, unbiased estimate of the mass based on previous spectroscopic data combined with the orbital inclination deduced from the phase-dependent linear polarization modulation. The dashed lines indicate the infrared/radio range of observed mass-loss rates; all the present estimates fall essentially between these limits. This would not be the case if errors in $\dot{M}$ were much larger than those estimated above. A correlation between $\dot{M}$ and M appears to emerge, in the same sense as in Abbott *et al.* (1986), although the noise level appears to be much higher in the polarization-based data. Unfortunately, using our estimate of the mass for HD 152270, this star now falls somewhat out of line with the overall $\dot{M}$-M correlation. In particular, the O component mass of this system is only 14 ± 5 $M_\odot$ based on polarization (St.-Louis *et al.* 1987), in $\sim 1\ \sigma$ agreement with the earliest spectral types of O stars (08/09) in the surrounding cluster NGC 6231, but barely in agreement with its O5–8 spectral type from van der Hucht *et al.* (1981), and certainly at odds with the O5 type given by Seggewiss (1974). If the O component is a late O star, its high luminosity implies that it would be a giant star. The fact that the scattering material does not lie preferentially on a line joining the two stars (Luna 1982; St.-Louis *et al.* 1987), suggests an anomaly that may invalidate the basic assumptions here of spherical symmetry around the W-R star. This will affect $\dot{M}$ but not M

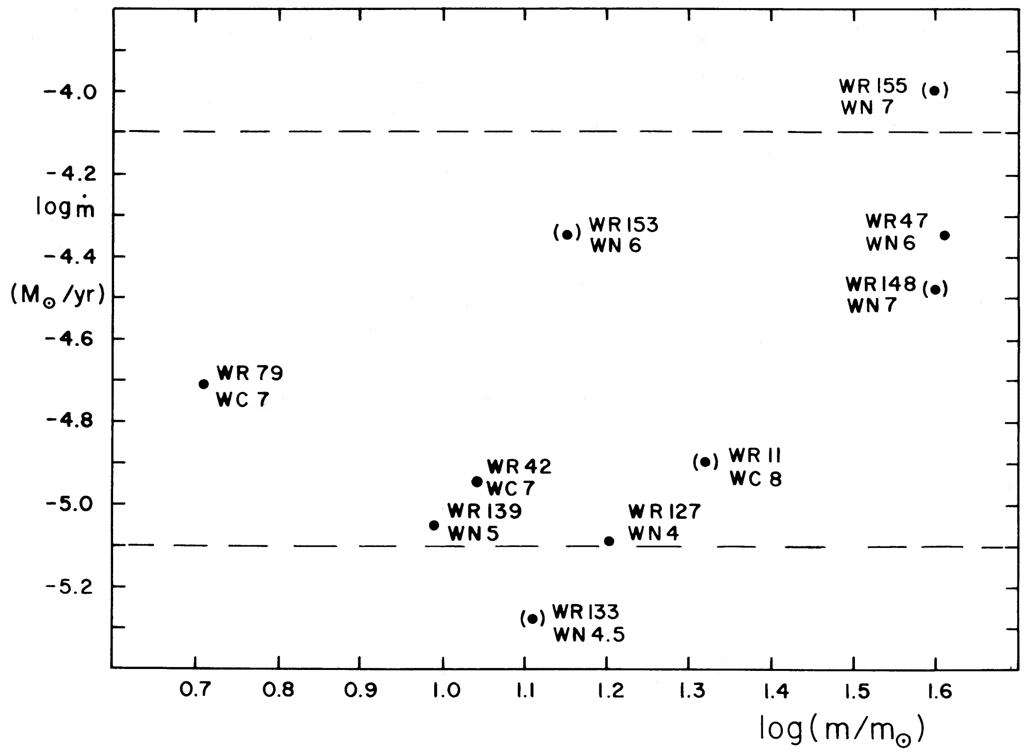

FIG. 12.—Mass-loss rates estimated in this paper by the linear polarization data as a function of the stellar mass for 10 W-R stars. The dashed lines indicate the observed range of $\dot{M}$ obtained from the free-free flux at infrared and radio wavelengths. The vertical bar indicates the 2 σ estimate.

for the W-R star, since the determination of i does not require such symmetry. On the other hand, a strong asymmetry would adversely affect the emission-line RV orbit, something which is not at all obvious in the observations (see Seggewiss 1974). If there are problems with the emphemeris of this star (extrapolated from 1971 to 1986) the above remarks would not necessarily apply. We believe that it is too early to draw definite conclusions concerning this star at present.

A least-squares fit of the form $\log \dot{M} = c_1 + c_2 \log M$ was made to the data in Figure 12, with M arbitrarily taken as the independent variable. Giving equal weights to all the data points yields a slope $c_2 = 0.80 \pm 0.39$; omitting WR 79, $c_2 = 1.28 \pm 0.43$, while taking only the four best systems, WR 42, 47, 127, and 139, gives $c_2 = 1.11 \pm 0.36$. Applying the same procedure to the data used by Abbott *et al.* (1986) in their Figure 7, gives $c_2 = 2.27 \pm 0.38$, similar to their value of c_2. An overall dependency $\dot{M} \propto M^{1-2}$ is compatible with most of the data. Such a relation is likely a consequence of fundamental $\dot{M} - L$ and $L - M$ relations for W-R stars (see Abbott *et al.* 1986).

We now compare the individual mass-loss rates obtained here by the polarization data with those deduced by other means. The most reliable way to obtain mass-loss rates is thought to be via radio free-free emission (see Barlow 1979). This method requires knowledge of the terminal velocity, the distance to the star, and the mean charge per ion. Regarding this last parameter, it has been stressed recently that the previous assumption that the ionization balance in the region of radio emission is the same as the ionization balance near the star could be wrong. Indeed, theoretical work by Nugis (1982), Schmutz and Hamann (1986), and Hillier (1987) shows that the wind could recombine to some extent between the two regions. This radio method for estimating the mass-loss rate also requires a positive radio detection, which limits the sample to close stars (see, Abbott *et al.* 1986).

Another way to estimate the mass-loss rate is from the infrared free-free flux ($\lambda = 10$ μm). Using a mean radio-infrared spectral index one can extrapolate and obtain an estimate of the radio flux and hence deduce the mass-loss rate (see Barlow 1979). This method requires knowledge of the same parameters as in the radio method but is less restrictive in distance.

The new derivation presented in this paper also requires the determination of several basic parameters characterizing the W-R star, such as the terminal velocity and the core radius (although the latter has only a small influence on the result except for very close systems). The fraction of light from the companion star must also be known, in addition to the orbital separation. Future models should attempt to allow for opacity effects near the surface of the W-R star; we only use a crude approximation (optically thick inside $R' = \varepsilon R_*$, thin outside) based mainly on the eclipse curve of one star (V444 Cygni). Other improvements would be to allow for the nonfinite size of the O star and the distortions of the W-R wind caused by the massive companion. Finally, this method is limited to stars in binary systems. We note, however, that Abbott *et al.* (1986) found no systematic difference in mass-loss rates between W-R stars in binary systems and those thought to be single.

We present in Figure 13 the mass-loss rates deduced with the polarization data versus the rates obtained with the radio fluxes (Abbott *et al.* 1986, their Table 6) and the infrared fluxes (Barlow, Smith, and Willis 1981) for the four stars in common. For HD 193576 = V444 Cygni, which can be considered to be a test object because its mass-loss rate is quite reliably known from its rate of period change (Khaliullin, Khaliullina, and Cherepashchuk 1984); $\dot{M}_{\rm WR} = (1.02 \pm 0.20) \times 10^{-5}\ M_\odot\ {\rm yr}^{-1}$.

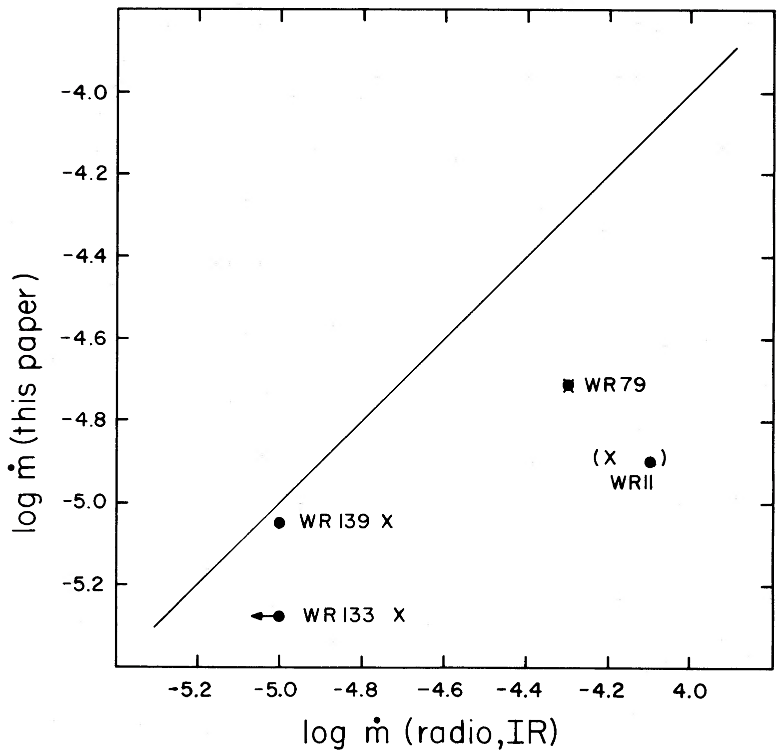

FIG. 13.—Comparison of the present polarimetrically derived mass-loss rates ($M_\odot$ yr^{-1}) with those derived from IR (*crosses*) and radio (*filled circles*) observations for stars in common. The straight line shows a perfect correlation.

The polarimetric, radio, and dynamic values for this star coincide very well.

Among the other three stars, we note a somewhat less satisfactory agreement: the polarization data yield values of $\dot{M}$ that are lower than those of the radio data by a factor 2.5 for HD 152270 (WR 79, already noted as problematic with regard to its mass determined from polarization) and by a factor 6 for HD 68273 (WR 11; its wide elliptical orbit renders the polarization-derived $\dot{M}$ less certain); for HD 190918 (WR 133), only an upper limit is available from the radio data. Whether these discrepancies are truly anomalous or not is difficult to assess at present. It would be extremely beneficial to obtain further, reliable *dynamical* determinations based on period changes.

V. SUMMARY

In this paper we have presented linear polarization data for five Galactic WN stars: two double-line binaries HD 186943 and HD 211853, that show a double-wave modulation of the two Stokes parameters Q and U with orbital phase, and three suspected single-line binaries HD 177230, 209 BAC, and HD 187282, for which we fail to detect any organized, phase-dependent variation. For HD 186943, we find an orbital inclination of $i = 55^\circ.7 \pm 8^\circ.2$. This value leads to masses of $M(\text{W-R}) = 16 \pm 5\ M_\odot$ and $M(\text{O}) = 35 \pm 11\ M_\odot$. For HD 211853, we obtain an inclination of $i = 78^\circ.2 \pm 1^\circ.0$. Unfortunately, the masses cannot be accurately determined for this star because of the perturbation of the WR + O_1 spectrum by the O_2 + O_3 system. Using the best estimates for $M \sin^3 i$ we find $M(\text{W-R}) = 14{:}\ M_\odot$ and $M(\text{O}) = 26{:}\ M_\odot$. The other three stars fit very well the correlation presented in Paper II between the rms scatter in polarization and the terminal velocity of the wind.

We have also presented a new method for deriving mass-loss rates for W-R stars in binary systems. We estimate the typical uncertainties of $\dot{M}$ to be $\pm 40\%$. This method is based on the amplitude of the mean locus described in the Q-U plane. The mass-loss rates that we have calculated for the five W-R stars presented in Papers I and III and five other W-R stars analyzed elsewhere correspond well with the observed *range* of mass-loss rates determined with the infrared and radio free-free emission fluxes (see Abbott and Conti 1987), although relatively large differences may prevail for some individual objects. The correlation between $\dot{M}$ and M found by Abbott *et al.* (1986) also seems to be confirmed, although at a higher noise level. Moreover, our method can reproduce the mass-loss rate of V444 Cygni, which is based on reliable dynamical arguments.

The present method for deriving mass-loss rates is not, as the radio method is, limited to close ($\lesssim 3$ kpc) stars. The main disadvantage of the polarimetric method is that one is limited to well-studied binaries. On the other hand, the polarimetric method samples the inner wind, which is less plagued by uncertainties in ionization level than is the radio/IR method, which samples the outer zones of the wind.

We are particularly grateful to S. Tapia for his encouragement and the use of the Minipol polarimeter. The polarimeter is supported by NSF Grant INT 82-13103 and Grant No. CW 0006–85 from the Space Telescope Science Institute. We thank the referee, D. C. Abbott, for constructive comments. A. F. J. M. and P. B. acknowledge financial support from the Conseil de Recherche en Sciences Naturelles et Génie du Canada.

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.
Antokhin, I. I., Aslanov, A. A., and Cherepashchuk, A. M. 1982, *Soviet Astr. Letters*, **8**, 395.
Aspin, C., Simmons, J. F. L., and Brown, J. C. 1981, *M.N.R.A.S.*, **194**, 283 (ASB).
Barlow, M. J. 1979, in *IAU Symposium 83, Mass Loss and Evolution of O-type Stars*, ed. P. S. Conti and C. W. H. de Loore (Dordrecht: Reidel), p. 119.
Barlow, M. J., Smith, L. J., and Willis, A. J. 1981, *M.N.R.A.S.*, **196**, 101.
Brown, J. C., McLean, I.S., and Emslie, A. G. 1978, *Astr. Ap.*, **68**, 415. (BME).
Castor, J. I., Abbott, D. C., and Klein, R. I. 1975, *Ap. J.*, **195**, 488.
Castor, J. I., and Lamers, H. J. G. L. M. 1979, *Ap. J. Suppl.*, **39**, 481.
Cherepashchuk, A. M., Eaton, J. A., and Khaliullin, K. F. 1984, *Ap. J.*, **281**, 774. (CEK).
Davis, A. B., Moffat, A. F. J., and Niemela, V. S. 1981, *Ap. J.*, **244**, 528.
Drissen, L., Lamontagne, R., Moffat, A. F. J., Bastien, P., and Seguin, M. 1986*a*, *Ap. J.*, **304**, 188.
Drissen, L., Moffat, A. F. J., Bastien, P., Lamontagne, R., and Tapia, S. 1986*b*, *Ap. J.*, **306**, 215.
Drissen, L., St.-Louis, N., Moffat, A. F. J., and Bastien, P. 1987, *Ap. J.*, **322**, 888 (Paper II).
Fraquelli, D. A., Bolton, C. T., and Horn, J. 1987, in preparation.
Friend, D. B., and Abbott, D. C. 1986, *Ap. J.*, **311**, 701.
Ganesh, K. S., Bappu, M. K. V., and Natarajan, V. 1967, *Kodaikanal Obs. Bull.*, **184**, A93.
Hillier, D. J. 1987, *Ap. J. Suppl.*, **63**, 947.
Hutchings, J. B., and Massey, P. 1983, *Pub. A.S.P.*, **95**, 151.
Khaliullin, K. F., Khaliullina, A. I., and Cherepashchuk, A. M. 1984, *Soviet Astr. Letters*, **10**, 250.
Lamontagne, R. 1983, Ph. D. dissertation, Université de Montréal.
Lamontagne, R., Moffat, A. F. J., and Seggewiss, W. 1983, *Ap. J.*, **269**, 596.
Leung, K.-C., Moffat, A. F. J., and Seggewiss, W. 1983, *Ap. J.*, **265**, 961.
Luna, H. C. 1982, *Pub. A.S.P.*, **94**, 695.
Lundström I., and Stenholm, B. 1984, *Astr. Ap. Suppl.*, **58**, 163.
Massey, P. 1981, *Ap. J.*, **244**, 157.
Massey, P., and Conti, P. S. 1980, *Ap. J.*, **242**, 638.
Moffat, A. F. J., Lamontagne, R., and Seggewiss, W. 1982, *Astr. Ap.*, **114**, 135.
Moffat, A. F. J., and Seggewiss, W. 1987, *Messenger*, No. 49, p. 26.
Moffat, A. F. J., and Shara, M. M. 1986, *A.J.* **92**, 952.
Moffat, A. F. J., Vogt, N., Paquin, G., Lamontagne, R., and Barrera, L. H. 1986, *A.J.*, **91**, 1386.
Münch, G. 1950, *Ap. J.*, **112**, 266.
Niemela, V. S., Conti, P. S., and Massey, P. 1980, *Ap. J.*, **241**, 1050.
Nugis, T. 1982, in *IAU Symposium 99, Wolf-Rayet Stars: Observations, Physics, Evolution*, ed. C. W. H. de Loore and A. J. Willis (Dordrecht: Reidel), p. 127.
Piirola, V. 1988, in *Polarized Radiation of Circumstellar Origin*, ed. G. V. Coyne, A. M. Magalhaes, A. F. J. Moffat, R. Schulte-Ladbeck, S. Tapia, and D. T. Wickramasinghe (Rome: Vatican Observatory), in press.
Robert, C., Moffat, A. F. J., Bastien, P., Drissen, L., and St.-Louis, N. 1988*a*, in preparation.
Robert, C., Moffat, A. F. J., Seggewiss, W., and Bastien, P. 1988*b*, in preparation.
Rublev, S. 1975, in *IAU Symposium 67, Variable Stars and Stellar Evolution*, ed. V. E. Sherwood and L. Plaut (Dordrecht: Reidel), p. 259.
Rudy, R. J. 1978, *Pub. A.S.P.*, **90**, 688.
St.-Louis, N., Drissen, L., Moffat, A. F. J., Bastien, P., and Tapia, S. 1987, *Ap. J.*, **322**, 870 (Paper I).
Schmidt-Kaler, 1982, *Landolt-Börnstein, New Ser., Group 6*, Vol. **2b**, ed. K. H. Hellwege (Berlin: Springer-Verlag), p. 1.
Schmutz, W., and Hamann, W.-R. 1986, *Astr. Ap.*, **166**, L11.
Seggewiss, W. 1974, *Astr. Ap.*, **31**, 211.
Stickland, D. J., Bromage, G. E., Budding, E., Burton, W. M., Howarth, I. D., Jameson, R., Sherrington, M. R., and Willis, A. J. 1984, *Astr. Ap.*, **134**, 45.
Torres, A. V., Conti, P. S., and Massey, P. 1986, *Ap. J.*, **300**, 379.
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.
Wilson, O. C. 1948, *Pub. A.S.P.*, **60**, 385.

PIERRE BASTIEN, LAURENT DRISSEN, ANTHONY F. J. MOFFAT, and CARMELLE ROBERT: Département de Physique, Université de Montréal, C.P. 6128, Succ. A, Montréal, P.Q. H3C 3J7, Canada

NICOLE ST.-LOUIS: Department of Physics and Astronomy, University College London, Gower St, London WCIE 6BT, England