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POLARIMETRY OF FOUR WOLF-RAYET STARS

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ABSTRACT

We present optical linear polarization observations of one well-established (W-R 151) and three suspected (W-R 3, W-R 103, and W-R 131) Wolf-Rayet binaries. The observations cover a time period of 2 weeks. The time variability of the data is analyzed by a χ^2 statistical test. Our measurements of W-R 3 (WN3+a, SB1) and W-R 131 (WN7 + a) indicate that the polarization was constant during the observing period within the observational errors. The polarization of W-R 103 (WC9, SB1?) is confirmed as being variable. While two published sets of polarization data showed incoherent variability, a preferred symmetry plane was indicated during our run. W-R 103 has been known before to show irregular photometric variability and we consider a common origin for the polarimetric variability. Our data do not support the binary nature of the three suspected binaries. However, we cannot rule out periods longer than the observing runs. W-R 151 (WN5+O8 V) is discovered to show phase-dependent polarization variations. Using the canonical model for binary polarization, i.e., scattering by free electrons located symmetrically about the orbital plane, the orbital inclination derived from the polarimetric data is $i \approx 74° \pm 5°$, while previous spectroscopic observations yielded $i \geq 50°$. Applying the polarimetrically derived value for the inclination, we now obtain masses of about 6 $M_\odot$ for the WN 5 star and 14 $M_\odot$ for the O8 star. This is the smallest mass deduced so far for a WN star. Our new data are discussed in conjunction with published polarization observations for binary as well as single Wolf-Rayet stars.

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

I. INTRODUCTION

The goal of polarization observations of Wolf-Rayet (W-R) binaries is to improve our knowledge on the masses of W-R stars. The mass is the most fundamental parameter of any star, since it determines its evolution. W-R stars are commonly accepted to be descendants of massive stars. Various evolutionary scenarios, which differ largely in the mass of the progenitor, have been considered possible by theorists, namely: (1) mass loss and transfer in massive binaries, (2) mass loss and mixing causing O stars to evolve into W-R stars directly (also referred to as Conti's scenario), and (3) mass loss and mixing causing O stars to evolve into W-R stars via the red supergiant phase. A thorough review of these evolutionary schemes is given in Chiosi and Maeder (1986). According to an estimate by Maeder (1981), of 10 W-R stars in the solar neighborhood, two may result from mixing and main sequence mass loss, three may be in the post–red supergiant stage and as many as five may result from binary mass transfer. The binary evolution may therefore represent an important channel for the production of W-R stars.

Binaries, preferentially eclipsing ones, are always the most reliable sources of mass determinations. Massey (1981) derived masses between 10 $M_\odot$ and 50 $M_\odot$ from a sample of 13 double-lined W-R binaries using spectroscopic observations. However, his mass determinations are affected by the usual factor of $\sin^3 i$ and Massey publishes minimum masses ($M \sin^3 i$) as well as mass estimates derived after assigning probable values to either the inclination or the mass of the O-type companion. The orbital inclination, i, can in principle be derived by means of polarimetry. The polarization is generally considered to be produced by electron (Thomson) scattering in an optically thin ionized envelope. The theory has been discussed in detail by Brown, McLean, and Emslie (1978). The model predicts harmonic variations of the Stokes parameters with phase, which depend on the inclination i. This method has previously been successfully applied to W-R binaries. In the recent past, the most noticeable results were provided by a polarization survey of bright W-R stars (St.-Louis *et al.* 1987; Drissen *et al.* 1987; St.-Louis *et al.* 1988 and references therein), which also included W-R binaries.

The present paper aims to identify more W-R binary systems with polarization variations. For the double-lined W-R stars with O-type companions, the polarimetry can be combined with spectroscopic radial velocity solutions to derive more reliable masses for both stars. In the single-lined W-R stars and in W-R stars with absorption lines, the discovery of periodic polarization variations may provide additional evidence for their binary nature.

We here present polarimetric observations of four W-R stars. The history of the objects is outlined in § II. In § III, details of the observing procedure and reduction are provided. The polarimetric results are presented in § IV, and the presence and nature of polarimetric variability with time is investigated. The results are discussed in § V, first for the individual stars and then in relation to other polarimetrically observed W-R stars. Our conclusions are drawn in § VI.

II. THE TARGET STARS

The four target stars were selected on the basis of presence of absorption lines in their spectra and/or spectroscopic and photometric variability. The stars are listed in Table 1, with catalog data from van der Hucht *et al.* (1981, 1988). Note that double-lined W-R binaries are commonly referred to as SB2's,

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TABLE 1

Target Stars

W-R	HD/Name	Spectral Type	v	$b-v$	Binary Type	Binary Period (d)	$v_0 - M_v$	z (pc)
3.........	9974	WN3+a	10.70	−0.06	SB1[a]	46.85?	12.7	−257
103.........	164270	WC9	9.01	0.03	SB1?[b,c]	1.754?	12.0	−217
131.........	IC 14-52	WN7+a	12.36	0.73	...	...	14.8	+275
151.........	CX Cep	WN5+O8V	12.37	0.65	SB2e[d]	2.1267	13.9	+145

[a] Moffat *et al.* 1986.
[b] Moffat, Lamontagne, and Cerruti 1986.
[c] van Genderen and van der Hucht 1986.
[d] Massey and Conti 1981*b*.

while single-lined W-R stars are called SB1's, and W-R stars with absorption lines are denotated WR + a.

a) *W-R 3*

Undisplaced hydrogen absorption lines in W-R 3 have been suspected as early as 1940 by Wilson. Massey and Conti (1981*b*) observed the object for over 400 days. They found essentially the same constant velocity as Wilson (1940) and Bracher (1966), but also a relatively small emission-line-to-continuum ratio. In addition to nitrogen and helium, hydrogen is in emission. Massey and Conti suggested that the H absorption lines are more likely intrinsic to the WN star. Moffat *et al.* (1986), with additional spectroscopy, found a possible radial velocity (RV) period $P = 46^{d}.85 \pm 0^{d}.02$, the absorption lines moving in phase with the emission lines. Their RV solution yields a mass function $f(m) = 0.2\ M_{\odot}$. The displacement from the galactic plane is $z = -257$ pc (van der Hucht *et al.* 1988). As Moffat *et al.* point out, this could suggest that W-R 3 is a runaway object harboring a compact companion.

The IR energy distribution of W-R 3 is indicative of free-free emission by stellar wind (Allen, Swings, and Harvey 1972; Cohen, Barlow, and Kuhi 1975). The object was part of a polarization survey by Hiltner (1956).

b) *W-R 103*

On the basis of spectroscopic and photometric variations, Moffat, Lamontagne, and Cerruti (1986) concluded that W-R 103 has SB1 status with a period of $P = 1^{d}.754$. However, van Genderen and van der Hucht (1986) using Walraven photometry of superior accuracy (0.002 mag) found no cyclic but just random variations of the order of 0.1 mag, which are most likely of intrinsic nature. The only clear non intrinsic variations known for W-R 103 are those found by Lundström and Stenholm (1982) and Massey, Lundström and Stenholm (1984), indicative of eclipse phenomena with a period of at least 17.7 yr.

W-R 103 has a stellar wind with a terminal velocity of $v_{\infty} =$ 1300–1400 km s^{-1} (van der Hucht, Conti, and Willis 1982; Torres, Conti, and Massey 1986) and with a C/He number abundance ratio of about 0.2 (Torres 1988; Smith and Hummer 1988). IR photometry shows hot (1500 K) carbon dust being formed continuously in the stellar wind, at an inner radius of about 220 R_* and with a dust-formation rate of $5.2 \times 10^{-9}\ M_{\odot}$ yr^{-1} (Williams, van der Hucht, and Thé 1987*a*).

Polarization measurements of W-R 103 by St.-Louis *et al.* (1987) show variations, but no indication of periodicity. The authors suggest the observed polarization variability to be caused by random wind asymmetries.

c) *W-R 131*

The presence of absorption lines in the spectrum of this WN7 star was reported by van der Hucht *et al.* (1981). No radial velocity measurements have been performed as yet. The object is located in the amorphous H II region L69.80 + 1.74, which is surrounded by dust clouds (Chu and Treffers 1981; Chu, Treffers, and Kwitter 1983). No polarimetric observations are available in the literature to date.

d) *W-R 151*

The eclipsing binary nature of this object was discovered by Hiltner (1948). Massey and Conti (1981*a*) improved the RV solution to find $M \sin^3 i$ (WN5) = 5.3 $M_{\odot}$ and $M \sin^3 i$ (O8 V) = 12.2 $M_{\odot}$. They estimated an inclination $i \geq 50°$. De Greve, Hellings, and van den Heuvel (1988), in a binary evolutionary study involving mass exchange, found $i = 51°$ but an uncertainty in their analysis is caused by lack of knowledge of the precise value of the mass-loss rate of the WN5 component.

Polarization observations were reported by Hiltner (1949, 1951). In his 1949 paper, Hiltner also observed CQ Cep in two filters at 4200 Å and 5300 Å and found that the polarization is independent of wavelength. He claimed an interstellar origin of the polarization of W-R stars, since he was unable to detect polarization modulated with the binary phases (and thus discovered interstellar polarization).

III. OBSERVATIONS AND COMMENTS ON THE DATA REDUCTION

The observations were obtained between 1987 June 30 and July 13, at the 1.23 m telescope of the German-Spanish Astronomical Center, Calar Alto, near Almeria, Spain. The polarimeter used is a two-channel polarimeter with an achromatic half-wave plate that rotates at a frequency of 50 Hz. Details of the instrument are given in Proetel (1987). Frequent rotation of the half-wave plate in combination with frequent sky chopping allow for the polarimeter to be operated as two single-channel polarimeters even under not quite photometric conditions. We started out the observing run using a 21″ diaphragm and later switched to a 15″ diaphragm when the brightness of the sky background increased due to the moonlight. Some remarks concerning the weather and moonlight conditions are given in the data tables (see below).

Our initial intention was to use a *B* filter for the observations and add up the results in the two channels. This had to be abandoned due to a sensitivity loss of the instrumentation as compared to previous observing runs (possibly caused by ice on the photomultiplier windows or aging of the multipliers) and the hazy sky. Instead, we carried out the observations with no filter. The passbands of the observations are therefore defined by the multiplier responses and the optics. The response curves of the two RCA multipliers are not available at the observatory. We did not attempt to derive the passband observationally considering the loss of valuable observing time.

In order to determine and monitor the instrumental polarization and the instrumental efficiency and to derive the zero point of the position angle in the equatorial coordinate system, we frequently observed both unpolarized and highly polarized standard stars. The results of our standard star data are given in Table 2. The data for the two channels, channel A and channel B, are given separately. We use intensity normalized Stokes parameters and our notation is

$$Px = Q/I = P \cos(2\Theta) \quad (1)$$

$$Py = U/I = P \sin(2\Theta) \quad (2)$$

where I, Q, U are the Stokes parameters, Θ is the position angle of the plane of vibration and P is the percentage polarization. We shall refer to the polarization components in the two channels as $Px(A)$, $Py(A)$, $Px(B)$, and $Py(B)$. The errors are denotated ΔPx and ΔPy, respectively. The errors are determined by the instrument software in two ways. A complete integration cycle is split (through input from the observer) into a number of n subintegrations. These are used to compute the mean errors of the means, i.e. $\{\sum_i [P(x, y)_i - P(x, y)_{\text{mean}}]^2/n(n-1)\}^{1/2}$, for the Px and Py components, respectively. Of course, if the number of subintegrations spent on the object is small, the calculated error is uncertain. Parallel to each measurement the error is predicted from photon counting statistics. Under photometric conditions, the ratio of calculated-to-predicted errors is a good indicator for a reliable measurement. A thorough discussion of the calculated errors will be carried out in § IV*a*.

As zero standards we used nearby stars from the Gliese (1969) catalog, which have very small interstellar polarization. These stars are bright, as most polarimetric standards are. Since we used no filter for our observations, we had to insert a neutral density filter in order to avoid damaging the photomultipliers. Only one object (Gl 823) has a brightness which made it accessible both with and without neutral density filter, with reasonable integration times. As can be seen in comparison to the data sets with filter, the neutral density filter introduces significant polarization [of about $Px(A)_{\text{ND}} = 0.29\%$, $Py(A)_{\text{ND}} = -0.14\%$, $Px(B)_{\text{ND}} = 0.19\%$, $Py(A)_{\text{ND}} = -0.09\%$]. The instrumental polarization is actually determined by only one measurement, but the errors are quite small and the stability of the instrument as monitored by the other standard star measurements was good. The corrections for instrumental polarization are given by

$$Px(A)_0 = Px(A) - (0.08 \pm 0.02)\% \quad (3)$$

$$Py(A)_0 = Py(A) - (-0.01 \pm 0.02)\% \quad (4)$$

$$Px(B)_0 = Px(B) - (-0.02 \pm 0.02)\% \quad (5)$$

$$Py(B)_0 = Py(B) - (0.04 \pm 0.02)\% . \quad (6)$$

The highly polarized standard stars are stars which have large interstellar polarization. The interstellar polarization is

TABLE 2

POLARIZATION RAW DATA OF THE STANDARD STARS

Julian Date 2,446,900+	Channel A				Channel B				Remarks
	Px	ΔPx	Py	ΔPy	Px	ΔPx	Py	ΔPy	
Schulte OB2 No. V12									
77.58049	−3.12	0.02	−6.65	0.02	−3.24	0.02	−6.02	0.02	Dia. = 21″
78.61410	−3.17	0.02	−6.65	0.02	−3.13	0.02	−6.02	0.03	Dia. = 21″
79.56130	−3.11	0.03	−6.62	0.03	−3.09	0.02	−5.98	0.03	Dia. = 21″
84.51324	−3.04	0.03	−6.61	0.03	−3.06	0.03	−5.94	0.03	Dia. = 15″
85.38177	−3.03	0.05	−6.54	0.04	−3.07	0.04	−5.99	0.04	Dia. = 15″
85.57919	−3.08	0.04	−6.57	0.04	−3.06	0.04	−5.95	0.04	Dia. = 15″
90.48064	−3.03	0.03	−6.61	0.03	−3.05	0.03	−5.99	0.04	Dia. = 15″
HD 14433									
79.63310	−1.87	0.04	−2.89	0.06	−2.05	0.05	−2.75	0.06	Neutral Density
80.62444	−1.85	0.03	−2.91	0.04	−2.08	0.03	−2.78	0.04	Filter, Dia. = 21″
Gl 765									
79.52315	0.27	0.03	−0.16	0.03	0.17	0.04	−0.07	0.04	Filter, Dia. = 21″
Gl 850									
84.53558	0.30	0.02	−0.17	0.02	0.22	0.02	−0.09	0.02	Filter, Dia. = 15″
Gl 823									
78.45056	0.08	0.02	−0.01	0.02	−0.02	0.02	0.04	0.02	Neutral Density
78.49949	0.31	0.04	−0.12	0.04	0.27	0.04	−0.02	0.04	Filter, Dia. = 21″
Gl 651									
78.38820	0.31	0.02	−0.16	0.02	0.17	0.02	−0.14	0.02	Neutral Density
78.63917	0.32	0.03	−0.12	0.03	0.18	0.03	−0.13	0.03	Filter, Dia. = 21″
79.37401	0.23	0.03	−0.13	0.03	0.23	0.03	−0.08	0.03	Filter, Dia. = 21″
80.42532	0.31	0.02	−0.13	0.02	0.22	0.02	−0.08	0.02	Filter, Dia. = 21″
81.37313	0.29	0.02	−0.16	0.02	0.18	0.03	−0.12	0.03	Filter, Dia. = 21″
82.49668	0.28	0.02	−0.18	0.02	0.18	0.03	−0.08	0.02	Filter, Dia. = 21″
83.55226	0.31	0.02	−0.10	0.02	0.16	0.03	−0.10	0.03	Filter, Dia. = 21″
84.37476	0.30	0.02	−0.13	0.02	0.15	0.02	−0.06	0.02	Filter, Dia. = 21″
84.38850	0.30	0.02	−0.10	0.03	0.20	0.03	−0.08	0.03	Neutral Density
86.44740	0.29	0.02	−0.16	0.03	0.19	0.03	−0.04	0.03	Filter, Dia. = 15″
88.49087	0.21	0.03	−0.10	0.03	0.17	0.03	−0.14	0.03	Filter, Dia. = 15″
90.36237	0.22	0.02	−0.17	0.03	0.25	0.03	−0.10	0.03	Filter, Dia. = 15″

described by Serkowski's law (Serkowski, Mathewson, and Ford 1975)

$$P(\lambda) = P(\lambda)_{max} \exp [K \ln^2 (\lambda_{max}/\lambda)] , \quad (7)$$

where K is a constant and $P(\lambda)_{max}$ is the maximum of the polarization observed at the wavelength λ_{max}. The interstellar percentage polarization shows a pronounced wavelength dependence. Comparing, e.g., the results for Cyg OB 2 Schulte 12 from Table 2 in channel A and channel B, it becomes apparent that the two channels differ by more than the instrumental polarization corrections. We attribute this to the different wavelength ranges and sensitivities of the two channels. Without information on the passbands we are unable to determine the instrumental efficiency. Laboratory measurements carried out in 1985 gave efficiencies larger than 98.5% in the range from 3500 Å to 6000 Å and above 99% beyond 6000 Å out to 1 μm.

The highly polarized standard stars are also used to derive the transformation of the position angle to the equatorial system. Schulte 12 is known to display a slight rotation of its position angle with wavelength (Schulz 1980). We assume here an intrinsic position angle of 116°. The second standard, HD 14433, is one of Serkowski's (1974) standards and its position angle is 112°. Note that there is also an error on how well these values have been determined for the standard stars, of $\Delta P \leq \pm 0.1\%$ and $\Delta\Theta \leq \pm 1°$. Therefore, errors in the position angle of program stars are commonly not given to an accuracy of better than $\pm 1°$. The position angle corrections are described by

$$\Theta(A)_{equ} = \Theta(A)_0 - (6° \pm 1°) \quad (8)$$

$$\Theta(B)_{equ} = \Theta(B)_0 - (5° \pm 1°) . \quad (9)$$

Equations (3)–(6) and (8)–(9) give the reduction steps that need to be applied to the raw data. As will be explained in § IV, for what we are interested in here it is not necessary to reduce the data.

IV. RESULTS

The results of our program star observations are listed in Table 3. Note that we are presenting the raw data. Publication of the raw data for the standard and program stars allows for the data analysis to be reproduced by other investigators. Also,

TABLE 3

POLARIZATION RAW DATA OF THE PROGRAM STARS

Julian Date 2,446,900+	Channel A				Channel B				Remarks
	Px	ΔPx	Py	ΔPy	Px	ΔPx	Py	ΔPy	
W-R 3									
80.59242	−2.35	0.05	−0.45	0.05	−2.49	0.06	−0.45	0.06	Dia. = 21″
83.57873	−2.36	0.05	−0.57	0.05	−2.46	0.05	−0.38	0.05	Dia. = 21″
84.56938	−2.42	0.04	−0.47	0.04	−2.45	0.04	−0.36	0.04	Dia. = 15″
88.58409	−2.23	0.05	−0.53	0.06	−2.42	0.09	−0.24	0.09	Dia. = 15″
90.53628	−2.36	0.05	−0.53	0.05	−2.44	0.05	−0.47	0.05	Dia. = 15″
W-R 103									
77.54028	−0.06	0.02	−0.76	0.02	−0.17	0.02	−0.76	0.03	Dia. = 21″
78.54595	0.07	0.03	−0.78	0.03	−0.02	0.03	−0.73	0.03	Dia. = 21″
79.49049	0.03	0.03	−0.80	0.03	−0.07	0.04	−0.82	0.04	Dia. = 21″
80.49397	0.09	0.03	−0.88	0.03	−0.04	0.03	−0.78	0.03	Dia. = 21″
82.47630	0.00	0.07	−0.74	0.04	−0.11	0.08	−0.73	0.04	Dia. = 21″, cloudy sky
83.52111	0.08	0.10	−0.78	0.03	0.02	0.11	−0.80	0.03	Dia. = 21″, moon descend.
84.49242	0.05	0.05	−0.76	0.03	−0.03	0.03	−0.81	0.03	Dia. = 15″
85.49296	0.09	0.07	−0.72	0.06	0.07	0.09	−0.79	0.06	Dia. = 15″, haze + moon
90.42547	0.18	0.03	−0.75	0.03	0.19	0.04	−0.76	0.04	Dia. = 15″, haze + moon
90.50465	−0.10	0.05	−0.79	0.04	−0.04	0.04	−0.73	0.04	Dia. = 15″, haze + moon
W-R 131									
78.41514	0.57	0.07	1.61	0.08	0.36	0.08	1.61	0.09	Dia. = 21″
79.46020	0.64	0.08	1.70	0.07	0.60	0.09	1.62	0.07	Dia. = 21″
80.45587	0.60	0.11	1.72	0.07	0.32	0.12	1.68	0.10	Dia. = 21″
81.41008	0.26	0.17	1.89	0.12	0.42	0.11	1.70	0.14	Dia = 21″, cloudy sky
84.46516	0.51	0.06	1.81	0.07	0.58	0.07	1.77	0.10	Dia. = 15″
88.55725	0.25	0.10	1.66	0.10	0.40	0.12	1.74	0.12	Dia. = 15″
90.45501	0.34	0.07	1.79	0.07	0.26	0.09	1.63	0.09	Dia. = 15″
W-R 151									
77.62647	−0.82	0.06	5.86	0.11	−0.95	0.07	5.80	0.12	Dia. = 21″
78.57696	−1.10	0.06	6.06	0.06	−1.04	0.07	6.03	0.06	Dia. = 21″
79.41588	−1.21	0.09	6.25	0.09	−1.18	0.11	6.07	0.11	Dia. = 21″
79.59869	−0.98	0.06	6.24	0.07	−0.94	0.07	6.25	0.08	Dia. = 21″
80.54329	−1.35	0.06	6.15	0.06	−1.27	0.07	6.08	0.07	Dia. = 21″
81.55750	−1.20	0.12	6.24	0.21	−1.30	0.13	6.16	0.21	Dia. = 21″, cloudy sky
83.46278	−1.18	0.13	5.95	0.09	−1.24	0.13	5.97	0.10	Dia. = 21″, cloudy sky
83.61595	−1.25	0.06	6.15	0.07	−1.24	0.07	6.11	0.08	Dia. = 15″, cloudy sky
84.41910	−1.37	0.10	5.98	0.10	−1.26	0.11	5.96	0.11	Dia. = 15″
84.61850	−1.25	0.06	6.17	0.17	−1.16	0.07	6.05	0.17	Dia. = 15″
85.44706	−1.39	0.13	5.84	0.16	−1.17	0.14	6.10	0.15	Dia. = 21″
85.61536	−0.86	0.12	5.67	0.11	−0.87	0.10	5.56	0.13	Dia. = 15″
88.51986	−1.39	0.09	6.02	0.11	−1.16	0.11	5.95	0.11	Dia. = 15″
88.61912	−1.34	0.08	5.89	0.09	−1.29	0.11	5.98	0.10	Dia. = 15″
90.38889	−0.97	0.09	5.88	0.09	−1.07	0.11	5.85	0.11	Dia. = 15″, moon rising
90.58130	−1.10	0.07	5.93	0.06	−1.00	0.07	5.87	0.07	Dia. = 15″, moon rising

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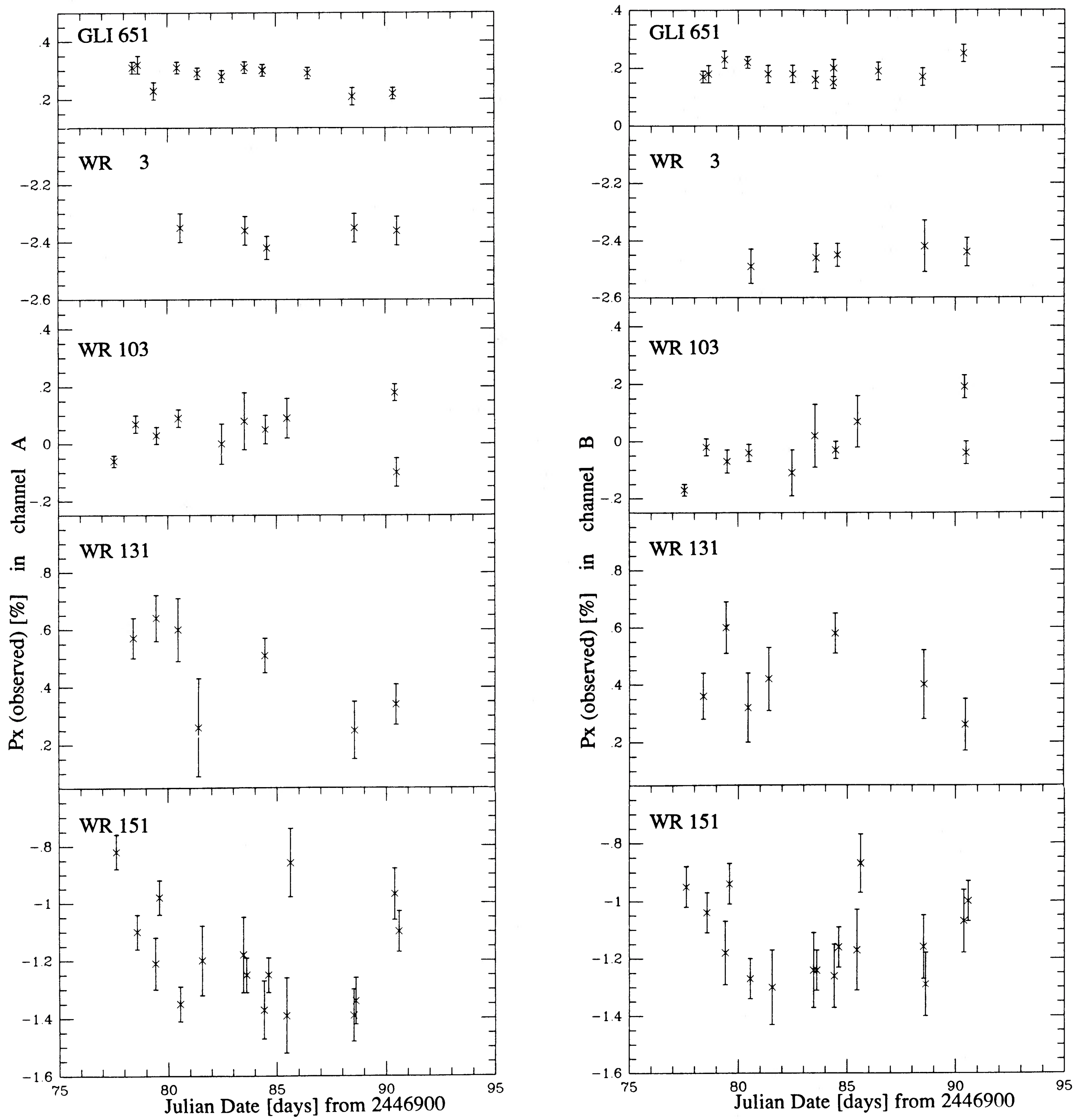

FIG. 1.—(*a–d*) The intensity normalized Stokes parameters, *Px* and *Py*, are plotted as a function of Julian Date. The polarimeter used is a double-channel instrument, and we obtained two sets of polarization data, in channel A and in channel B. The ordinate has the same scale for all stars so that the data are more readily comparable. As we are interested in polarimetric variability we display for comparison in the top panel the data of a standard star, Gl 651, that should be constant. Also, any significant variations that seem to be present in channel A occurred in channel B as well. Note the significant change that took place during the last night in the *Px* component of W-R 103 on a time scale of hours.

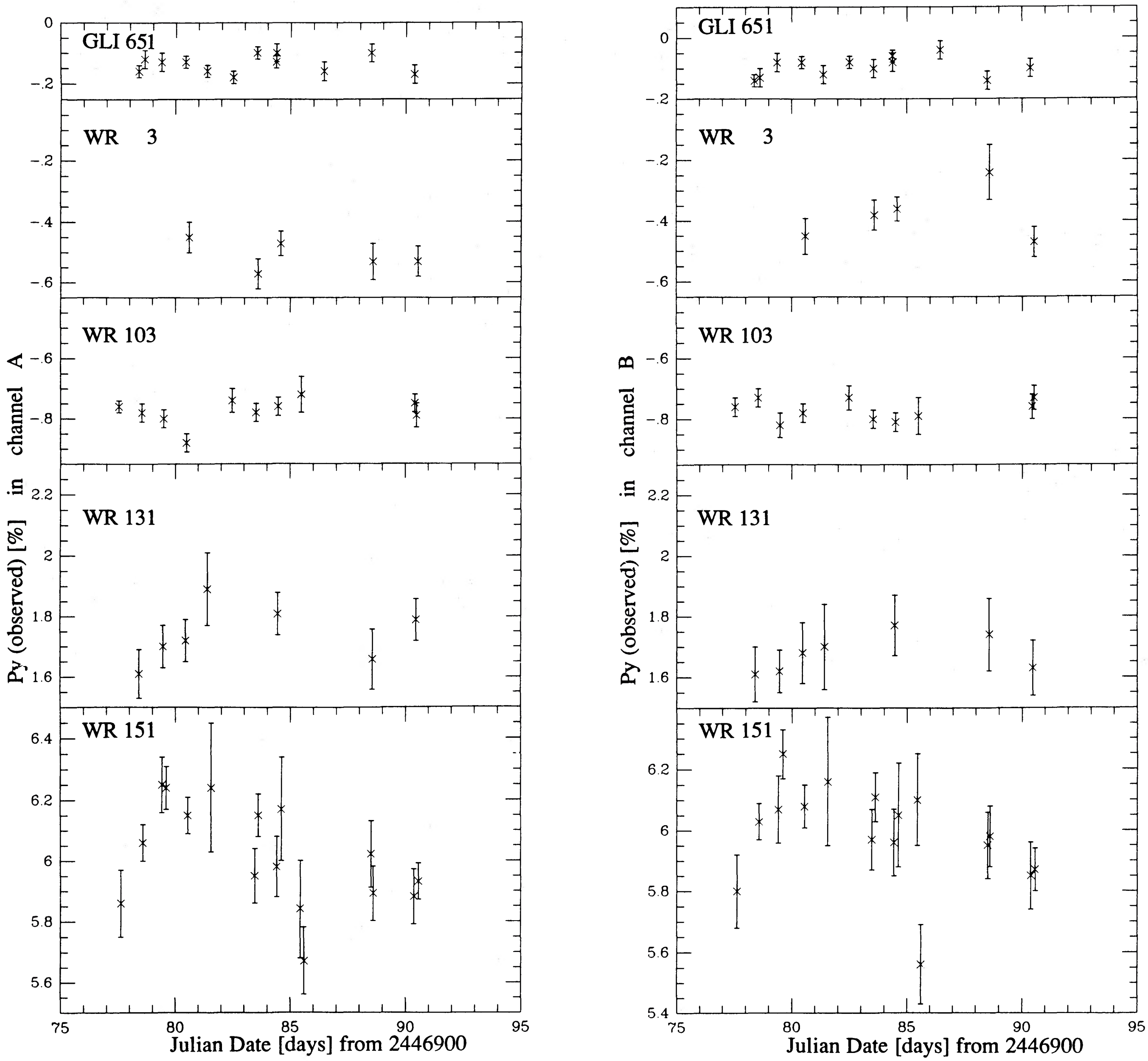

FIG. 1—*continued*

we are mainly interested in the polarization *variations*, not in the absolute values. In doing the full reduction, we should have to propagate the measured and inherent errors of the standard star polarizations. This would increase the formal uncertainties on the program star data, especially since almost all polarization standards have turned out to be variable (Bastien *et al.* 1988) at the level of accuracy attained here. For the statistical analysis of the program stars' polarization variations we are, however, interested in the actual measurement errors of the data. The binary inclination is determined from the shape of the locus described by Px and Py during an orbital cycle (Brown, McLean, and Emslie) and is unaffected by a rotation or translation of the coordinate frame to which Px and Py are referred. Therefore, it is not necessary to know the displacement of the instrumental zero point and position angle (or the interstellar polarization).

In Figure 1(*a*–*d*), we display the polarization observations as a function of time. The four parameters $Px(A)$, $Px(B)$, $Py(A)$, $Py(B)$ are displayed versus Julian date for the program stars and for the most frequently measured zero polarization standard Gl 651. The ordinate has the same scale for all stars, so that the observations are more readily comparable. The $\pm 1\ \sigma$ error bars are quite small for the standard and the bright W-R stars, but increase to the fainter W-R stars. Despite the different size error bars, the polarization of W-R 103 and W-R 151 appears variable compared to the standard star. The fact that

TABLE 4

χ^2 TEST FOR POLARIZATION VARIABILITY

		Channel A				Channel B				
		Px		*Py*		*Px*		*Py*		
Name	*n*	χ^2/f	$P(\chi^2)$	χ^2/f	$P(\chi^2)$	χ^2/f	$P(\chi^2)$	χ^2/f	$P(\chi^2)$	Variable
GLI 651	12	2.503	*0.997*	1.458	*0.853*	1.347	*0.807*	1.587	*0.904*	No
W-R 3	5	0.485	*0.253*	1.022	*0.605*	0.151	*0.039*	1.728	*0.852*	No
W-R 103	10	6.563	*1.000*	1.784	*0.931*	8.428	*1.000*	0.943	*0.520*	Yes
W-R 131	7	3.009	*0.992*	1.122	*0.651*	2.217	*0.959*	0.419	*0.136*	No
W-R 151	16	5.839	*1.000*	3.151	*1.000*	2.542	*1.000*	2.315	*0.995*	Yes

we have measurements in two channels comes in handy at this point, because any trustworthy variation must occur in channel A and channel B.

In order to find out whether our program stars are polarimetrically variable, we have to compare the observed polarization variations to the calculated errors of the individual observations. If the variations are significantly larger than the errors, the object is considered variable. This question is best attacked in a quantitative way, by applying a statistical test to the data.

a) χ^2 Test for Polarization Variability

In each channel, A or B, we have a set of *n* observations, Px_i, Py_i, $i = 1, 2, \ldots, n$. The value of χ^2 is calculated in the following way

$$\chi^2 = \sum [(Pi - P)/\Delta Pi]^2 \quad (10)$$

with

$$P = (\sum Pi/\Delta Pi^2)/(\sum 1/\Delta Pi^2) \quad (11)$$

and

$$\sum = \sum_{i=1}^{n}, \; Pi = Px_i \text{ or } Py_i, \; P = Px \text{ or } Py,$$

and

$$\Delta Pi = \Delta Px_i \text{ or } \Delta Py_i .$$

The probability $P(\chi^2)$ that the observed χ^2 is less than a value χ^2 if the measurement errors are normally distributed was calculated by integrating the χ^2 distribution with $f = n - 1$ degrees of freedom. In Table 4, we give for each channel and parameter *n*, χ^2/f (the expected value of χ^2/f is 1), and $P(\chi^2)$ for the standard star Gl 651 and for the four observed W-R stars. Adopting a 99% confidence level, stars with two or more values of $P(\chi^2)$ greater than 0.99 are considered variable. This is the case for W-R 151, where all four parameters give values above 0.99. For W-R 103 only two values are greater than 0.99. However, these occur in the same parameter, *Px*. The fact that the variation is observed in both channels further supports its reality. The polarization of W-R 103 is also considered to be variable. The polarization of Gl 651, W-R 3, and W-R 131 did not vary significantly during the period of observation. The uncertainties as calculated from the square roots of the reduced χ^2 for the percentage polarizations of these stars are Gl 651: 0.02%, W-R 3: 0.01%, and W-R 131: 0.02% (the two channels gave the same results to within the quoted digit). These uncertainties give an indication as to at what level the above stars did not vary.

b) The Polarization Model for W-R 151

The polarization of W-R 151 shows significant variations with time. In this section, we shall describe the polarization using the canonical model and determine the binary inclination.

Px(A), *Py(A)*, *Px(B)*, and *Py(B)* of W-R 151 are plotted against orbital phase, Φ, In Figures 2*a*, *b*. The orbital phase was calculated from a period of $P = 2^{\mathrm{d}}.1267$ and the time of conjunction with the W-R star in front T_0 = JD 2,443,768.63 (Hiltner 1948). These ephemeris were also used by Massey and Conti (1981*a*), who presented a mass estimate based on spectroscopic studies (see also § V*c*). For the polarization model, we assume that two point sources are revolving about each other in a circular orbit and are scattering off an optically thin, corotating, common envelope of electrons. Following Brown, McLean, and Emslie, the polarimetric data are fitted to a Fourier series up to second-order terms

$$P = p_0 + p_1 \cos \lambda + p_2 \sin \lambda + p_3 \cos 2\lambda + p_4 \sin 2\lambda , \quad (12)$$

with $P = Px$ or Py, $p_i(i = 0, \ldots, 4) = p(x)_i$ or $p(y)_i$, and $\lambda = 2\pi\Phi$. The coefficients were found as a result of least-squares fitting of the data to the above equation. The measurements were weighted by the observational errors. The coefficients and their standard deviations, σ, together with the χ^2/f values for the fits are presented in Table 5. Here, the number of degrees of freedom, $f = n - N - 1$, equals 10 since we have $n = 16$ data points of each parameter in each channel and fit $N = 5$ coefficients. The χ^2/f are not impressively good. Clearly, our 16 data points with their moderately large observational errors are only a first attempt. The fits are also illustrated in Figures 2*a*, *b*. The fits in channel A do bear

TABLE 5

HARMONIC COEFFICIENTS FOR THE FITS OF W-R 151

	p_0 $\pm\sigma$	p_1 $\pm\sigma$	p_2 $\pm\sigma$	p_3 $\pm\sigma$	p_4 $\pm\sigma$	χ^2/f
			Channel A			
Px	−1.176	0.003	−0.075	0.066	−0.112	4.95
	0.027	0.044	0.025	0.038	0.027	
Py	5.974	0.106	0.018	−0.213	−0.057	1.60
	0.026	0.049	0.030	0.044	0.031	
			Channel B			
Px	−1.096	−0.031	−0.048	0.091	−0.073	2.33
	0.029	0.048	0.028	0.042	0.031	
Py	5.969	0.040	0.010	−0.138	−0036	2.28
	0.028	0.051	0.033	0.048	0.034	

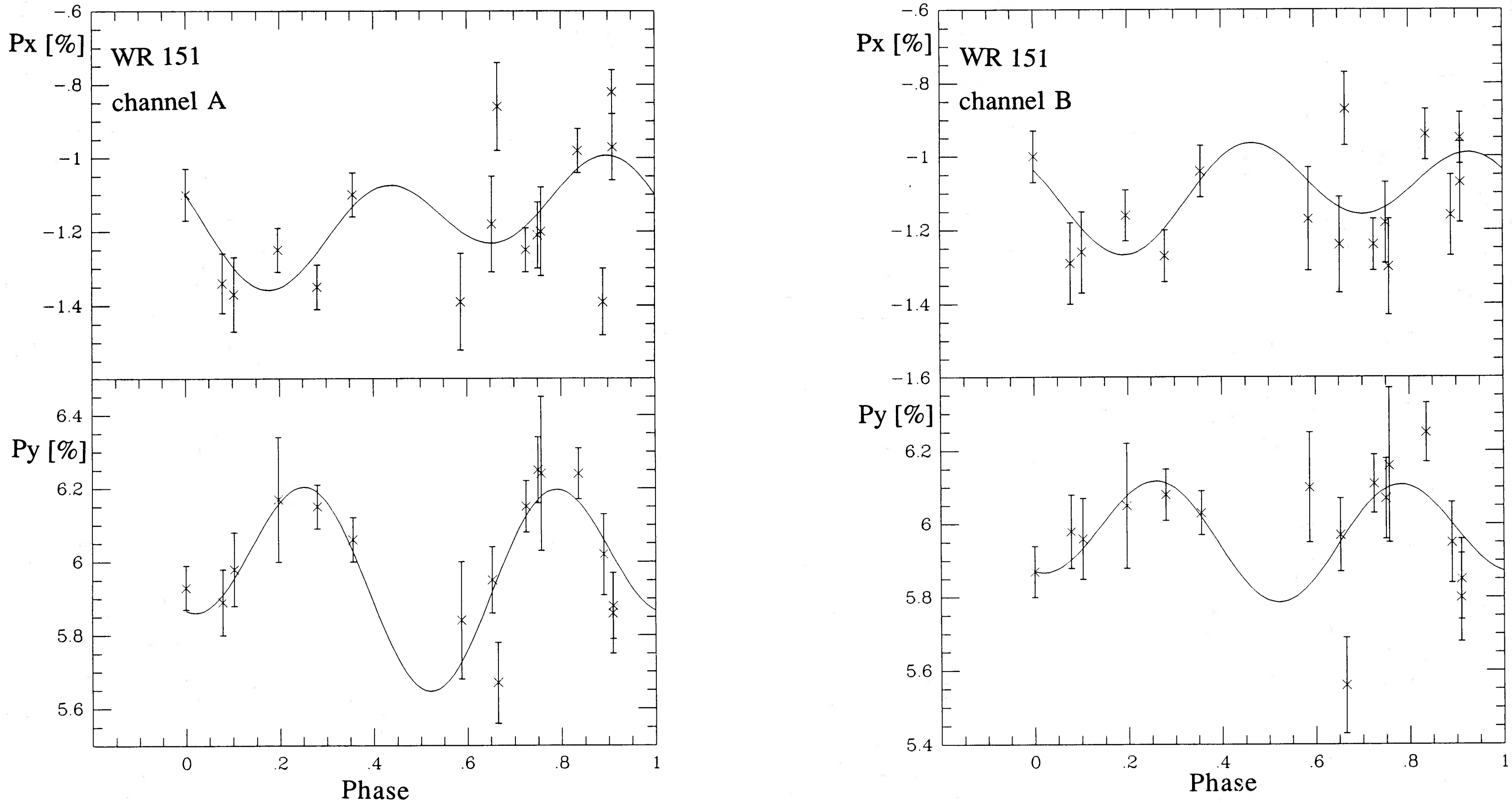

FIG. 2.—(*a*, *b*) The Stokes parameters of W-R 151 are plotted vs. binary phase for the two channels. The polarization clearly shows phase-dependent behavior. The solid lines represent fits with the canonical model for binary polarization. They were obtained by fitting the data to Fourier series up to second-order terms. The smallest deviations from the fit are computed for *Py* in channel A, as the naked eye readily sees. The measurement errors appear large, but are actually pretty good with regard to the apparent magnitude of this object. We attribute the differences of the fits to the *Py* data in channels A and B to the lack of data points in between phases 0.4 and 0.6 and the large variation of the three data points around phase 0.6. The phasing is the same in both channels. The offsets in the absolute values are due to the fact that these are unreduced data.

resemblance to the ones in channel B. In particular the phasing reproduces quite well. The minimum of the two fits in Py has a noticeably different depth. It clearly depends on the three data points around phase 0.6 and lack of observations corresponding to phases between 0.4 and 0.6.

From the coefficients of the fits, we can derive the binary inclination following equation (A1) of Drissen *et al.* (1986*a*):

$$(1 - \cos i/1 + \cos i)^4 = \{[p(y)_3 + p(x)_4]^2 + [p(y)_4 - p(x)_3]^2\}/\{[p(y)_4 + p(x)_3]^2 + [p(y)_3 - p(x)_4]^2\} \quad (13)$$

Again, the fact that we have two independent sets of observations is advantageous. We calculate the following orbital inclinations from the data in channel A: $i = 73°$ and in channel B: $i = 75°$. This agreement seems surprisingly good with respect to the quality of the fits. Giving equal weight to each fit would mean $i = 74° \pm 1°$.

In order to better judge the reliability of this result, we carry out an error estimate following Aspin, Simmons, and Brown (1981). This paper contains an analysis of the minimum required accuracy of polarization measurements in order to obtain the orbital inclination to $\pm 5°$ at a significance of 10%. In the case of W-R 151, with a typical error σ_0 of 0.1%, a mean amplitude A_0 as defined by equation (6) of Aspin *et al.* of 0.285% and a number N_0 of 32 data points in both channels together, we read from Figure 2 in Aspin *et al.* that the quoted accuracy can be expected for inclinations larger than about 75°. Hence, our observations have just about the right accuracy to yield a $\pm 5°$ error in the inclination. The large amplitude of the polarization variation helps.

In the case of noncorotation, harmonic terms higher than 2λ are expected to be present (see Brown, McLean, and Emslie). We have not carried out fits with higher harmonic terms, given the small number of data points. W-R 151 is well accepted to be an eclipsing system (see § II*c*). The presence of eclipses violates the point source assumption. Eclipses have the effect of suddenly enhancing the polarization during eclipses by reduction of the direct, unpolarized intensities. Again, the scarcity of our current data, especially around phase 0.5, does not allow us to comment on this effect.

V. DISCUSSION

The discussion section has two major parts: in § V*a*–*c*, we shall discuss the polarimetric results for the individual stars observed in this paper, whereas in § V*d*, we shall put our results in the broader context of polarization variations found in WR binaries in general.

a) W-R 3 and W-R 131

The polarization of the two suspected binaries W-R 3 and W-R 131 showed no significant variability over the course of our observing run. Polarization variability is our only criterion to distinguish intrinsic from interstellar polarization since we do not know the polarization spectrum. Hence, we must take into account the possibility that the observed polarization is mainly of interstellar origin. An estimate of the interstellar contribution can be obtained by examining the polarization of stars located spatially close to the program stars and having established values of their interstellar polarization.

For W-R 3, the distance modulus listed by van der Hucht *et al.* (1988) is 12.7 mag. In an environment of ± 10 mag in R.A., $\pm 3°$ in Decl. and with distance moduli of $11 \leq m - M \leq 13$, we find 31 stars which have their polarization measured. The data come mainly from the work of Hiltner (1956), and in a few cases from Hall (1958). The position angle distribution is shown in Figure 3. The position angles in the environment of W-R 3 are very well organized, they retain values of $(101 \pm 10)°$. Hiltner observed W-R 3 at a position angle of 95° and this value is indicated in Figure 3 by an arrow pointing at the corresponding bin. We conclude that the polarization of W-R 3 is probably mostly of interstellar origin. Only observations spanning the alleged period of 47 days could shed more light on this problem.

For W-R 131, van der Hucht *et al.* (1988) list a distance modulus of 14.8 mag. In a cube of ± 10 mag in R.A., $\pm 4°$ in Decl. and with distance moduli of $12 \leq m - M \leq 15$, we find 22 stars with measured polarization in the publications by Hiltner (1956), Hall (1958), and Appenzeller (1966). We reduced our observations of W-R 131 using the mean polarization and derive a position angle of about 32°. The position angle distribution is displayed in Figure 4 and the bin corresponding to the value for W-R 131 is again indicated by an arrow. Note the large bin sizes compared to Figure 3. As can be seen in Figure 4, the position angles have a chaotic distribution in this part of the Galaxy. They can assume values between 0° and 180°, with no single, preferred direction. In this case, the polarization in the environment of the W-R star is of no help in making a decision about its interstellar versus intrinsic nature. It is, however, apparent that position angles of around 30° to 40° do occur in the interstellar polarization. Only future observations of either the wavelength dependence or time variability on a longer time scale could reveal an intrinsic component to the polarization of W-R 131. In summary, we find no evidence that the observed polarization of W-R 3 or W-R 131 is truly intrinsic to the objects.

One might conclude that the absence of time variability of the polarization weakens the case for binarity in both objects. (A more detailed discussion of W-R systems that do not show phased polarization variations will be given in § V*d*) On the other hand, if we make the assumption that both objects are actually binaries that produce intrinsic polarization, one possible reason why our observations did not reveal them would be that the orbital periods are very long. The phase-locked polarization of a binary has four extrema during one orbital period. Obviously, our observations have not covered a single extremum in either system. We might use this fact to set lower limits on the periods, since one would expect the periods to be much longer than 4 times the time intervals covered by the observations, e.g., for W-R 3, $p \gg 40^{\mathrm{d}}$ and for W-R 131, $p \gg 48^{\mathrm{d}}$. At least for W-R 3 the alleged period of 47^{d} is not in contradiction with our results.

b) W-R 103

The case of W-R 103 has been discussed in detail by St.-Louis *et al.* (1987). The authors found the polarization to vary with time. They searched for periodicities in the polarization variations, with no success. Since the polarization varied in an irregular way and did not show a preferred symmetry axis or plane, they concluded that blob ejection in random directions from the W-R star is the most likely explanation. In Figure 5, we display our polarization data in the $Px - Py$ plane. Again, the polarizations in channel A and B are plotted separately. In order to denotate the time sequel of the data points, the first and last observations are identified by an A and an Ω, respectively. Contrary to the observations of St.-Louis *et al.*, it

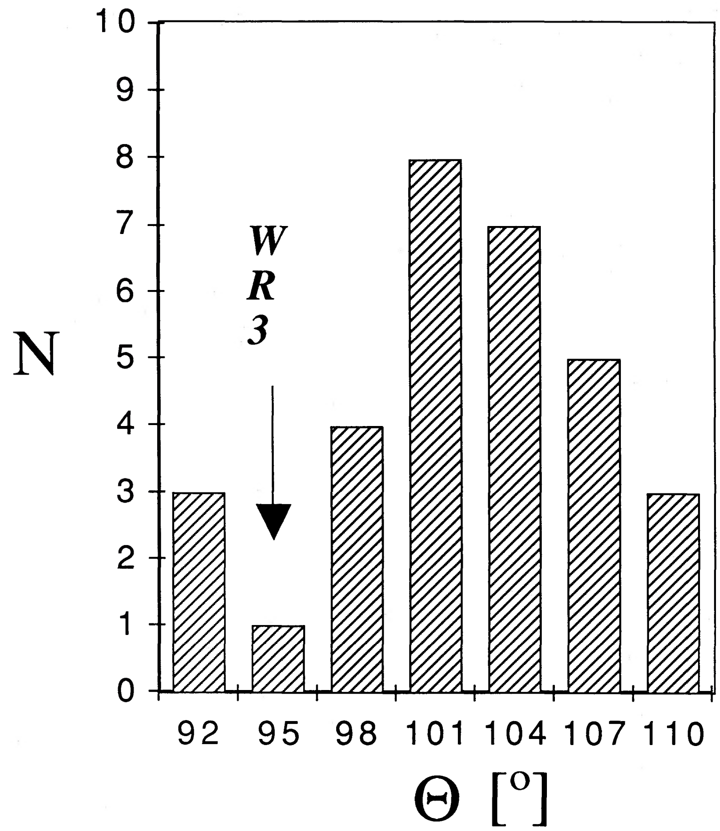

FIG. 3.—The number distribution of interstellar position angles in a volume around W-R 3 shows that the interstellar polarization vectors are very well aligned to within ±10°. The arrow indicates the position angle bin of W-R 3. Since the polarization of W-R 3 does not vary in time and its position angle agrees well with the interstellar value, the polarization at the time of our observations was mainly of interstellar nature.

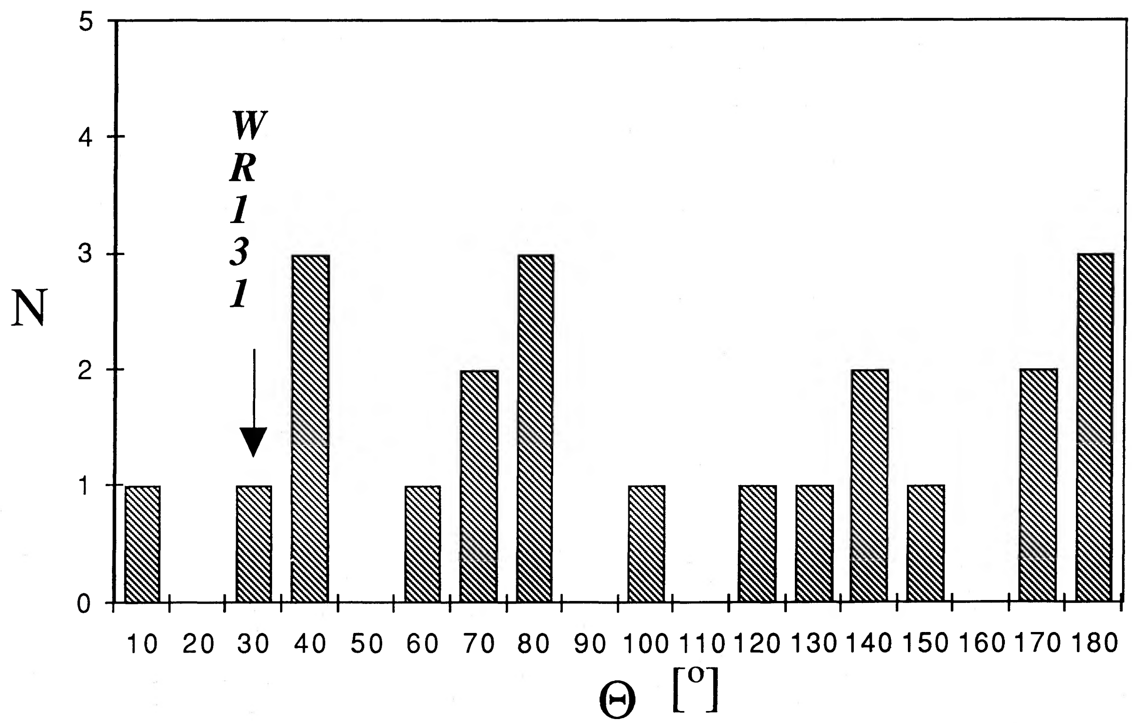

FIG. 4.—The number distribution of interstellar position angles in a volume around W-R 131 shows that the interstellar polarization vectors are not aligned in this part of the Galaxy. The arrow indicates the position angle bin of W-R 131. Although the polarization of W-R 131 was constant during our observing run, we cannot conclude to a predominantly interstellar origin. Position angles with similar values to the one measured in W-R 131 are, however, present in the interstellar polarization.

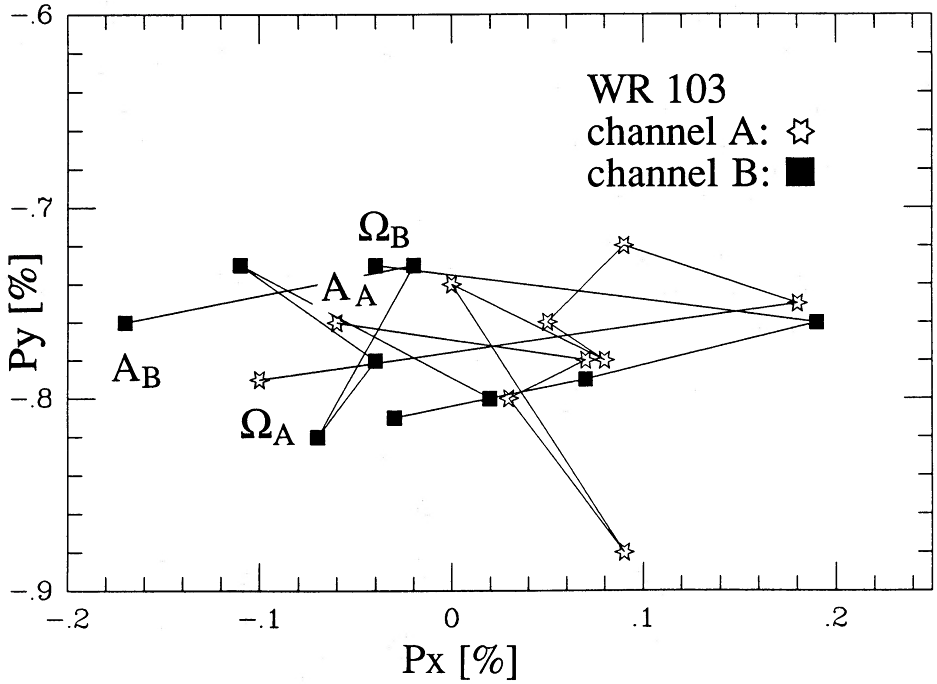

FIG. 5.—The observed polarization of W-R 103 in the two channels is plotted here in the Stokes parameter plane. Subsequent points have been linked and the beginning and end of each time path is indicated by the symbols A and Ω. The described paths suggest the presence of a preferred axis or symmetry plane for the polarization variations. (We did not plot the individual measurement errors to avoid confusion with the other lines in this diagram.)

appears that there is a preferred direction in our polarization observations. St.-Louis *et al.* observed W-R 103 on two occasions. Their first data set, taken at Steward Observatory, covered the observing period from JD 2,446,213.9 to 2,446, 221.9. The second data set was obtained between JD 2,446, 486.9 and 2,446,527.9 at Las Campanas, Chile. During both observing runs, a blue filter (λ_c = 4700 Å, FWHM = 1800 Å) was used. In order to compare our data to theirs, we have applied the reductions outlined in § III and then simply taken the mean of the two channels. Our bandpass is certainly different from theirs. For the intrinsic polarization of the W-R star itself, which is assumed to be caused by Thomson scattering and should therefore be independent of wavelength, different filters should yield the same polarizations. Because of the unknown amount of interstellar foreground polarization and the unknown contribution by dust scattering from the material that causes the infrared excess, the observed polarization might however have a wavelength dependence, in which case our observations might give slightly different values than those by St.-Louis *et al.* From a plot of all three data sets (not shown here), it seems that our own observations show just the "tip of the iceberg," the amplitude of the polarization variations being much larger in general. Taking all data together, the directionality disappears.

This does not contradict our above mentioned finding of a preferred axis. Suppose that at a given time a blob is formed in the wind of the W-R star that dominates the polarization. While the blob moves away from the star, the polarization will decrease but the *position angle will be constant* until another blob formed closer to the star will dominate the overall polarization. If that blob moves away from the star at a different angle, the position angle will switch to a new value and will then, again, remain constant until yet another blob takes over. We therefore also plotted the Las Campanas data position angles as a function of Julian date (not shown here). The percentage polarization in this data shows several spikes (see Fig. 4*c* of St.-Louis *et al.*), but the position angle changes are completely uncorrelated with these. However, the large variations in percentage polarization in themselves indicate that the polarigenic mechanism must affect large parts of the system on a time scale of days.

Another interesting feature of our polarization data, best visible in Figure 1, is that a significant polarization variation took place during the last night of our observing run, the data points being only hours apart. In summary, there may be significant changes in the polarization on time scales of hours to days, while the position angle may or may not vary synchronously at different points of time. Moreover, there is likely to be an extremely long binary period (see § II*b*), on which the short-time, irregular fluctuations in the polarization are superposed. Follow-up measurements on longer time scales then achieved so far are necessary to clarify this.

c) W-R 151

Our data is § IV*b* show that W-R 151 = CX Cep displays phase-dependent polarization variations. Using the canonical model for binary polarization, we have derived a value for the orbital inclination: $i = (74° \pm 5°)$. Massey and Conti (1981*a*) deduced $M(\mathrm{WN}) \sin^3 i = 5.3\ M_\odot$, $M(\mathrm{O}) \sin^3 i = 12.2\ M_\odot$, and $M(\mathrm{O})/M(\mathrm{WN}) = 2.34 \pm 0.21$. We thus obtain the following mass estimates:

$$M(\mathrm{WN}) = (6 \pm 1)\ M_\odot \quad \text{and} \quad M(\mathrm{O}) = (14 \pm 2)\ M_\odot .$$

This WN mass is the smallest WN mass found up to now. St.-Louis *et al.* (1988) list WN masses in the range $9.8 \leq M_{\mathrm{W\text{-}R}}/M_\odot \leq 41$.

At a v magnitude of 12.4 mag, W-R 151 is a fairly faint system for polarimetric observations. (Massey and Conti used a 4 m telescope for their spectroscopy.) A repetition of the polarimetric observations and, given the small number of available spectra, also of the spectroscopy, is highly desirable. If not smaller errors, at least more data points should be obtained. Although the system is quite faint, the large amplitude of the polarization variations allows a reasonably reliable value for the inclination to be derived, as was discussed above.

Massey and Conti in their paper come to the conclusion that it is very likely for at least the W-R star to fill its Roche lobe. Given the masses and the period, we can use Kepler's law to determine the separation, a, of the two stars for a circular orbit,

$$(M_{\rm WN} + M_{\rm O})[M_\odot] = a^3[{\rm AU}]/P^2[{\rm yr}] , \qquad (14)$$

and the value we get is roughly 19 $R_\odot$. We can now derive the Roche (mean) critical radii, R^*, for each star following Plavec (1968)

$$R^*_1[R_\odot] = a[R_\odot]\{0.38 + 0.2 \log (M_1/M_2)\} \qquad (15)$$

and the values become

$$R^*_{\rm WN} \approx 6\ R_\odot \quad \text{and} \quad R^*_{\rm O} \approx 9\ R_\odot .$$

For the O8 main-sequence star, the radius can be determined using the radiation law as we believe to know O star parameters with a certain degree of confidence. Using $\log T_{\rm eff} = 4.544$ and $\log L/L_\odot = 5.168$ from de Jager and Nieuwenhuyzen (1987) gives

$$R_{\rm O} \approx 10\ R_\odot$$

and the O star just about fills its Roche volume. The same can be said about the W-R star assuming the canonical radius of 10 $R_\odot$. Even if the sytem is not in contact (given the uncertainties in the estimates of the radii), it appears close enough so that the wind from the W-R star may be expected to be highly focused toward the O star companion, introducing asymmetry that in turn favors the production of polarized radiation with a phase-dependent modulation.

d) Summary of Polarization Observations and Suggestions for Future Work

i) *Binaries*

In this section, we shall summarize and compare the available polarimetric data and confront them with the current ideas concerning the evolution of W-R stars and the nature of their winds. In our Galaxy, we now know 157 W-R stars (van der Hucht *et al.* 1988, Table 4). Of these, all together 43 W-R binaries and W-R+a objects are known. A total of 23 or 53% of these have, to our knowledge, published observations of polarization variations. Table 6 summarizes the results. The character of the polarization variations is described for binaries and suspected binaries in part A of the table. For comparison, part B contains the single W-R stars. Note that since at the present time the observations cover time periods of days to about a month, Table 6 can only give information on the character of polarization variability on corresponding time

TABLE 6

POLARIZATION VARIABILITY IN WOLF-RAYET STARS

W-R	HD/Other	Type	Period[d]	Polarization Variability	Refs.	Photometric Amplitude ΔV[mag]	Refs.
				A. Binaries and Suspected Binaries			
3.........	9974	WN3+a (SB1)	46.85	None, polarization interstellar?	1	0.02	10
6.........	50896	WN5 (SB1)	3.76	Phase-locked	2	0.04	11
11.........	γ2 Vel	WC8+O9 I	78.50	Phase-locked	3		
21.........	90657	WN4+O4–6	8.26	Phase-locked	4		
22.........	92740	WN7+a (SB1)	80.35	Stochastic, no preferred axis	5	0.01	11
24.........	93131	WN7+a	...	Stochastic, no preferred axis	5	0.01	11
25.........	93162	WN7+a	...	Stochastic, preferred axis?	5	0.005	11
42.........	97152	WC7+O7 V	7.89	Phase-locked	3		
47.........	E311884	WN6+O5 V	6.34	Phase-locked	5		
48.........	Θ Mus	WC6+O9.5 I	18.34	Phase-locked?	3		
79.........	152270	WC7+O5–8	8.89	Phase-locked	3		
103.........	164270	WC9 (SB1?)	1.75	Stochastic, preferred axis?	1	0.1	12
123.........	177230	WN8 (SB1)	1.76	Stochastic, few data	6	0.06	10
124.........	209 BAC	[WN8]? (SB1)	2.36	Stochastic, no preferred axis	6	0.04	10
127.........	186943	WN4+O9.5 V	9.56	Phase-locked	6	0.03	10
128.........	187282	WN4 (SB1)	3.85	Variable, few data	6	0.03	10
131.........	IC14-52	WN7+a	...	None	1		
133.........	190918	WN4.5+O9.5 I	112.8	Phase-locked	6		
139.........	193576	WN5+O6	4.21	Phase-locked	7		
148.........	197406	WN7 (SB1)	4.32	Phase-locked	8	0.04	10
151.........	CX Cep	WN5+O8 V	2.13	Phase-locked	1		
153.........	211853	WN6+O	6.69	Phase-locked	6	0.04	10
155.........	214419	WN7 (SB1)	1.64	Phase-locked	9		
				B. Single Stars			
16.........	86161	WN8	None	Stochastic, preferred axis?	5	0.06	11
40.........	96548	WN8	None	Stochastic, large, no preferred axis	5	0.1	11
78.........	151932	WN7	None	Stochastic, no preferred axis	5		
90.........	156385	WC7	None	None, polarization interstellar?	3	<0.003	11
111.........	165763	WC5	None	None	3		

REFERENCES.—(1) This work; (2) McLean 1980; (3) St.-Louis *et al.* 1987; (4) Moffat and Seggewiss 1987; (5) Drissen *et al.* 1987; (6) St.-Louis *et al.* 1988; (7) Rudy and Kemp 1978; (8) Drissen *et al.* 1986*a*; (9) Drissen *et al.* 1986*b*; (10) Moffat and Shara 1986; (11) van Genderen, van der Hucht 1987, and Steemers 1987; (12) van Genderen and van der Hucht 1986.

scales. In other words, very short variations of the order of minutes to hours as well as long-term variations on time scales larger than a month cannot be discussed on the basis of this table. The data seem to indicate that there are basically four phenomenological categories of polarization behavior. The polarization may be correlated with phase, it may vary stochastically, but sometimes show a tendency for a preferred axis, it can be completely incoherent, or there may be no variations at all. An additional aspect of the variability not reflected in Table 6 is that the late subtypes, e.g. WC9 and WN8 stars show the largest polarization variations (Drissen *et al.* 1987). As Table 6 shows, these stars also display the largest photometric variations ($\Delta V > 0.05$ mag) as was discovered first by Weller and Jeffers (1979).

Phase-dependent polarization variations have been detected in 14 cases. All 11 observed of the 22 double-line spectroscopic binaries listed in Table 5A of van der Hucht *et al.* (1988) show phased polarization variations. Among these, the three binaries with O supergiant companions are a bit different in the sense that there is periodicity (although the case for Θ Mus is very weak), but also a superposed variability of stochastic character. Since these systems are all comparatively wide binaries, this component could originate in the wind of the O supergiant (see the discussion on γ^2 Vel and Θ Mus in St.-Louis *et al.* 1987), but as well in the wind of the W-R star itself (see the discussion on single stars below). Furthermore, the orbits of γ^2 Vel and W-R 133 have considerable eccentricity, compatible with the long periods. The determination of orbital inclinations is not as easy here as it is in the remaining eight cases, where the polarization variations are very well described by the canonical model for binary polarization and circular orbits. A table of inclinations and updated masses can be found in St.-Louis *et al.* (1988). The data are complete except for the new values derived in this paper for W-R 151, so we do not repeat them here. Using the 11 objects with improved masses, the average mass of a W-R star still amounts to about 20 $M_{\odot}$. Massey (1981) noted that W-R stars of similar subtypes can have different masses, thus denying a systematic connection between masses and subtypes. Abbott and Conti (1987) discuss the lack of a correlation between terminal wind velocity and WN subtypes and the spread of terminal velocities within a WN subtype and suggest that this might reflect a large range in luminosity and/or mass within a WN subtype, so that high- and low-gravity stars may have similar effective temperatures. For the WC sequence, on the other hand, the terminal wind velocity does correlate with subclass, in the sense that the later subtypes have slower winds and higher wind densities (van der Hucht, Cassinelli, and Williams 1986*a*, *b*). Massey furthermore noted that the masses of WC stars are not systematically smaller than the masses of WN stars. This is of interest for the idea that WN types might evolve into WC types. In the polarimetrically observed sample, we are dealing with too small numbers to do statistics. However, there is an indication that the earlier WN types and the WC types have smaller masses than the later WN types. Van der Hucht *et al.* (1988) concluded that WC stars descend only from the massive WN stars, i.e., the WNL stars. To address the problems outlined above, it is very important that all double-line WR binaries be observed polarimetrically.

In contrast to the double-line W-R binaries, the single-line and suspected W-R binaries show a variety of polarization behavior. In other words, all the four categories of variability can be found in the nondouble-line W-R stars. Let us first elucidate the classification of their types.

The best cases for binaries are those classed W-R + a (SB1), since a radial velocity solution is available from the emission lines and absorption lines are also observed in the spectra. The objects named W-R (SB1) have velocity solutions for the emission lines, but no absorption spectrum shows up. Furthermore, we have to distinguish two groups of single-line spectroscopic binaries, namely those with small mass functions, in which the unseen companion might be a compact star, and those with large mass functions. As was recently shown by De Greve *et al.* (1988), the massive single-line binaries may comprise W-R + B systems produced from very massive stars by stellar wind mass loss from the primary. The B star is unseen because of the magnitude difference of ≥ 2 mag between the W-R and the B star. A large magnitude difference might also result if the companion is an O star but the W-R star belongs to the luminous WN7 or WN8 subclass. For the late WN subtypes, which are thought to have dense winds, the absorption lines could, however, just as well be intrinsic to the W-R star. There is evidence that this is the case for W-R 3 (WN3 + a [SB1]; Moffat *et al.* 1986) and W-R 138 (WN 6 + a [SB1]; Schmutz, Hamann, and Wesselowski 1988). For the W-R (SB1) systems, there is about an equal chance for the variations to originate from the presence of a compact companion as to being intrinsic to the W-R star. The suggestion is that the W-R + compact binaries originate from the OB + W-R systems (van den Heuvel 1976) on the basis of evolutionary considerations.

Finally, there is a group of W-R + a objects, which are suspected of being binaries simply on the basis of presence of absorption lines in their spectra. Again, as in the case of the W-R + a (SB1) objects, we might expect massive binaries since the absorption lines are normally indicative of O-type companions, or WNL stars with intrinsic absorption lines, preferentially among the later subtypes. Note that none of the objects in this class listed in Table 6A has an orbital period assigned to it. Some of the WN + a objects, such as, e.g., W-R 24 and W-R 25 have been studied very carefully for radial velocity variations, with negative results so far (Moffat *et al.* 1986 and references therein). This rules out close, massive companions. One possibility however is that there are among them binaries with extremely long orbital periods and correspondingly small radial velocity amplitudes. The well-known W-R 140 (WC7 + O4–5) has an orbital period of 7.9 yr (Williams *et al.* 1987). Also suspected to have a long period of about 15 yr is W-R 137 (Williams, van der Hucht, and Thé 1987*b*). In W-R 25, the absorption lines are also indicative of an O-type star and Drissen *et al.* (1987) suspect another very long binary. At least some of the W-R + a stars might simply be binaries viewed pole-on so that their duplicity can just not be inferred from radial velocity studies. In summary, we have the following choices:

1. single-line W-R stars are intrinsically variable stars, periodicities may result, e.g., from pulsational or rotational effects;
2. they are long-period binaries with O-type companions and the radial velocity variations are very small;
3. they have unseen compact companions in the case of small mass functions, or massive companions but the orbital inclinations are very small;
4. they have unseen B-type companions in the case of large mass functions, or luminous WN stars, so the contrast to the O-type companion is high;
5. W-R + a systems may be binaries viewed pole-on.

With these possibilities in mind, we shall now return to discussing the polarimetric results. A suitable way to look at the

TABLE 7

POLARIZATION VARIABILITY VERSUS WR TYPE

W-R TYPE	$N_{obs}(N_{tot})$	POLARIZATION VARIABILITY TYPE I	II	III	IV
SB2	11 (22)	11	...	...	...
mSB1	2 (5)	1	...	1	...
lmSB1	7 (11)	2	1	3	1
W-R+a	3 (5)	...	1	1	1
Single	5 (114)	...	1	2	2

NOTE.—The polarization variability types are defined as I: phase-locked, II: preferred axis?, III: stochastic, IV: none.

polarization variability is given in Table 7. We use the common notations for double-line W-R binaries, SB2, and single-line W-R binaries with large, mSB1 and small mass functions, lmSB1 (Hidayat, Admiranto, and Vander Hucht 1984, updated through van der Hucht *et al.* 1988). Some of the polarization variability will be explained categorically, for some cases we have to look at the individual star in detail.

In order to get variable polarization from an object, we need to have (1) a significant fraction of the observed flux be scattered, (2) some lack of symmetry either in the illuminating source or in the distribution of scatterers, and (3) some intrinsic changes in these with time. Since W-R stars as a class have the highest known continuous mass-loss rates, their highly ionized winds are thought to provide the scatterers and the mechanism giving rise to polarization is generally considered to be electron scattering. It should be kept in mind, however, that most late-type WC stars show infrared excesses indicative of circumstellar dust. Whether or not dust scattering is important has yet to be studied through the wavelength dependence of the polarization, for which few data exist so far (Cohen and Kuhi 1977; Schmidt 1988). A beautiful sketch of two basic types of polarization behavior for W-R stars was presented in Moffat and Seggewiss (1987, Fig. 1). For a single W-R star surrounded by a spherically symmetric, homogeneous wind, the net intrinsic polarization is zero and the observed polarization corresponds to the interstellar polarization. This is very likely the case in the single W-R stars W-R 90 and possibly W-R 111 (see Table 6B). The double-line spectroscopic binaries have been discussed above. Basically, even if the electron distribution is symmetric around the W-R star, the presence of the O star provides sufficient light asymmetry to produce a net, phase-locked polarization.

Polarimetry is superior to spectroscopy in the case of a binary system viewed pole-on and this bears some results for the W-R + a objects. Whereas the radial velocities are constant in this case, the polarization is expected to show two full rotations of the position angle at constant percentage polarization per orbital cycle. This allows us to rule out short-period binaries with great confidence for the well-observed stars W-R 24 and W-R 25 and possibly also for W-R 131, where better time coverage should be achieved before a final conclusion is drawn. W-R 25 shows a tendency toward a preferred axis. If this is, as Drissen *et al.* (1987) note, related to the binary character of object, then we probably see it under a high inclination and the binary period must indeed be very long. Although all three objects harbor a WN7, their short-term polarimetric behavior is rather different. W-R 25 is of type II, W-R 24 of type III and the constant W-R 131 is classed type IV. There is one single WN7 star to which we can compare this behavior, WR 78, a type III. Since the single W-R stars show also a diversity of behavior and since the WN7 star in the W-R + a systems probably is the dominant light source, we might turn around the argument used in the case of W-R stars with O supergiant companions: The polarimetric variations observed in W-R + a objects are mainly caused by the W-R star itself. Whether or not certain W-R + a objects are binaries has still to be proved by long-term monitoring.

Among the single-line spectroscopic W-R(SB1) binaries, there are three cases for phase-locked behavior, namely W-R 6, W-R 148, and W-R 155. Excluding for the moment W-R 6, since a new study is under way (see Drissen *et al.* 1987), we are left with two WN7 systems. W-R 155 has a high mass function, while W-R 148 has a low mass function. One question is immediately apparent comparing these single-line WN7 objects to the WN7 + a stars discussed above. It should be expected that the magnitude difference is even larger between the WN7 star and its companion for the single-line stars, since not even the absorption lines of the companion have been seen. If the companion cannot provide enough photons, why does the phase-locked behavior occur at all? The answer is that all of the phase-locked polarization must originate from the W-R star itself. If the W-R star photons scatter off its own envelope, phase-locked variability will occur only if the scattering envelope has an asymmetry that is related to the binary motion. This is the case in contact systems, where the Roche surface is seen at different aspects during the binary orbit. Daniel (1981) described a star which nearly fills its Roche lobe by a prolate ellipsoid and his Monte Carlo study showed that the polarization and light variations depend on the orbital inclination. Indeed, W-R 155 and W-R 148 have small orbital separations (see St.-Louis *et al.* 1988) and they may be near-contact systems. The polarization data show that although binary modulation is present, there is significant scatter above the instrumental error around the fitted curve. This may well be caused by temporal variations in the WN7 stars' winds (see the discussion of nonsecond harmonic terms for W-R 155 in Drissen *et al.* 1986*b*), in accordance with our discussion of the WN7 + a and single WN7 stars above.

But what about those single-line W-R binaries that do not show phased polarization variability? When the orbital separation becomes large and the companion does neither contribute to the light nor does it gravitationally distort the wind of the W-R star, the systems behave as single stars. Again, the wide binary explanation is appealing. If this interpretation is correct, the short periods seen in W-R 103 and W-R 123 can consequently not be binary periods. Until long-term monitoring is available, the long-period binary versus single star question remains open.

ii) *Single W-R Stars*

As a point of interest we note that single O supergiants have been found to display incoherent polarization variations at the 0.2% to 0.4% level on time scales of days to months (Lupie and Nordsieck 1987), similar to what is now also observed in some single W-R stars. In the O stars, a correlation is apparent between the amplitude of the polarization variations and the rotational velocities of the stars, $v \sin i$.

Among the single W-R stars, the two stars with the largest known degree of stochastically varying polarization, i.e., W-R 40 and W-R 103 (i) are both late-type W-Rs (WN8 and WC9, respectively) meaning that they have the relatively highest wind densities (van der Hucht, Cassinelli, and Williams 1986*a*, *b*), and (ii) display both the largest degree of known short time scale photometric microvariations: $\Delta V \geq 0.1$ mag on a time scale of a few days (van Genderen and van der Hucht 1986; van Genderen, van der Hucht, and Steemers 1987).

Van Genderen *et al.* observed for W-R 40 and W-R 103 that these are bluer when brighter, and they related this to temperature effects in the observed pseudophotospheres. W-R wind densities are in most cases, and certainly in W-R 40 and W-R 103, sufficiently high to prevent the stellar layers with $v_{\rm wind} = 0$ km s^{-1} to be observed. Thus, for the observer $\tau = 1$ occurs at a radius where the wind has already reached a certain fraction of its terminal velocity. When the wind density, however, does not fall off with spherical symmetry, but suffers, e.g., from turbulence caused by differential rotation, then we look into deeper and hotter layers at certain positions than at other positions. As van Genderen *et al.* describe, turbulence can cause both eddies, in which we look deeper into hotter parts of the stellar wind, and vertical expulsion of blobs. Depending on the lifetime of these phenomena one may see them reappear during one or more revolutions of the star. With a typical W-R radius of 10 $R_\odot$, a variability time scale of one to two days would imply equatorial velocities in the range of 250–500 km s^{-1}. Such compare favorably with observed W-R absorption line widths of 150–500 km s^{-1} (Massey 1980; Massey and Conti 1981*a*, *b*). Assuming that only few of these phenomena occur on a W-R "surface" at a given time, the above sketched phenomena of eddies and blobs could explain the observed magnitude and colour changes. These phenomena should then preferably occur in the densest W-R winds like those of W-R 40 and W-R 103. Such inhomogeneous wind densities, and specifically the inhomogeneous electron densities, would thus also cause the large polarization variations observed in W-R 40 and W-R 103. The reappearance of certain features during several revolutions of the star could explain the presence of a preferred polarization axis at times.

VI. CONCLUSIONS

We have presented and discussed time-dependent broadband linear polarization observations of four W-R stars. On a time basis of days, W-R 3 and W-R 131 displayed no polarization variability above the measurement errors. The position angle of W-R 3 was furthermore consistent with the polarization being mainly of interstellar origin. The polarization of W-R 103 showed variations, in one night on a time scale of hours. While a preferred axis appeared to be present in our own data thus suggesting the presence of some symmetry axis retained over a time period of a few days, an earlier data set did not show this behavior. In this object, the significant variations in percentage polarization that occur every few days point to an underlying mechanism that affects large parts of the stellar wind. In general, the polarization of this proposed single-line binary system behaved as if the W-R star were a single star. We cannot rule out binaries having comparatively long periods, on the order of weeks to months, in the above objects. The polarization of W-R 151 showed a modulation with orbital phase that was used to derive, in combination with published spectroscopic data, an estimate of the WN5 and O8 star's masses, of 6 and 14 $M_\odot$, respectively. The object is a (near) contact binary system as a comparison of the Roche (mean) radii to the stellar radii demonstrated.

Information on polarization variability on a time basis of days is now available for about 53% of the W-R binaries and W-R + a objects. We introduced four phenomenological types of polarization variability, namely I: phase-locked II: preferred axis? (meaning that a preferred plane was indicated at times) III: stochastic, and IV: none.

The double-lined systems were all of type I, with on average little variations above the canonical model in close systems harboring main-sequence companions and with considerable scatter in the wider systems containing supergiant companions. The latter systems can also be considered as examples of how the individual polarizations of the two stars in their own winds tend to dominate the polarization of wider binaries. W-R + OV systems provide reliable masses and more such observations are needed to clarify issues related to the mass loss and evolution of W-R stars.

The single-line binaries showed all four types of polarimetrical behavior. Phase-locked variability was observed in at least two cases. The modulated variations in single-line systems may originate from the scattered W-R light in its own, tidally distorted wind. Long-period binaries with companions less luminous than the W-R star are expected to show only very small periodic polarization variations because the W-R star's wind is not gravitationally influenced and the companion does not contribute to the scattered photons. Therefore, W-R binaries with long periods are expected to behave polarimetrically as single W-R stars, as we consider indicated through the observation of type II to IV objects. Among the single-line systems, polarimetry provides a reliable method to identify more binaries. Polarimetry may therefore help to gain information on the true binary frequency.

In the three W-R + a systems observed so far, there is one of each except for the phase-locked polarimetry type. If the observed radial velocities are essentially constant, as e.g. in the well-studied W-R + a systems W-R 24 and W-R 25, polarimetry eliminates the possibility of a binary seen pole-on and hence rules out close, massive binaries with great confidence.

Few single W-R stars have so far been monitored polarimetrically. As of yet, they also display all kinds of polarimetric behavior except for type I. We found that the largest polarimetric variations are observed in the later subtypes, in which the photometric microvariability is also large and varies on similar time scales. We suggest that when the main wind layer from which we receive most of the continuum light has dynamical inhomogeneities, resulting in the formation of temporarily hotter eddies or blobs, changes in polarization are the consequence. When the fluctuations affect large parts of the winds, corresponding amplitude changes in the polarization are expected. If certain features occasionally remained spatially stable for several stellar revolutions, the appearance of preferred position angles in the polarization could be explained. This idea should be tested by further, preferably synchronous, photometric and polarimetric monitoring.

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REFERENCES

Abbott, D. C., and Conti, P. S. 1987, *Ann. Rev. Astr. Ap.*, **25**, 113.
Allen, D. A., Swings, J. P., and Harvey, P. M. 1972, *Astr. Ap.*, **20**, 333.
Appenzeller, I. 1966, *Z. Ap.*, **64**, 269.
Aspin, C., Simmons, J. F. L., and Brown, J. C. 1981, *M.N.R.A.S.*, **194**, 283.
Bastien, P., Drissen, L., Ménard, F., Moffat, A. F. J., Robert, C., and St.-Louis, N. 1988, *A.J.*, **95**, 900.
Bracher, K. 1966, Thesis, Indiana University.
Brown, J. C., McLean, I. S., and Emslie, A. G. 1978, *Astr. Ap.*, **68**, 415.
Chiosi, C., and Maeder, A. 1986, *Ann. Rev. Astr. Ap.*, **24**, 329.
Chu, Y.-H., and Treffers, R. R. 1981, *Ap. J.*, **250**, 615.
Chu, Y.-H., Treffers, R. R., and Kwitter, K. B. 1983, *Ap. J. Suppl.*, **53**, 937.
Cohen, M., Barlow, M. J., and Kuhi, L. V. 1975, *Astr. Ap.*, **40**, 291.
Cohen, M., and Kuhi, L. V. 1977, *M.N.R.A.S.*, **180**, 37.
Daniel, J.-Y. 1981, *Astr. Ap.*, **94**, 121.
De Greve, J. P., Hellings, P., and van den Heuvel, E. P. J. 1988, *Astr. Ap.*, **189**, 74.
De Jager, C., and Nieuwenhuyzen, H. 1987, *Astr. Ap.*, **177**, 217.
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.
van Genderen, A. M., and van der Hucht, K. A. 1986, *Astr. Ap.*, **162**, 109.
van Genderen, A. M., van der Hucht, K. A., and Steemers, W. J. G. 1987, *Astr. Ap.*, **185**, 131.
Gliese, W. 1969, *Catalogue of Nearby Stars* (*Astr. Rechen Inst. Heidelberg, Nr. 22*).
Hall, J. S. 1958, *Pub. US Naval Obs.*, **17**, 275.
Hidayat, B., Admiranto, A. G., and van der Hucht, K. A., 1984, *Ap. Space Sci.*, **99**, 175.
Hiltner, W. A. 1948, *Ap. J.*, **108**, 56.
———. 1949, *Ap. J.*, **109**, 471.
———. 1951, *Ap. J.*, **114**, 241.
———. 1956, *Ap. J. Suppl.*, **2**, 389.
Lundström, I., and Stenholm, B. 1982, in *IAU Symposium Number 99, Wolf-Rayet Stars: Observations, Physics, Evolution*, ed. C. W. H. de Loore and A. J. Willis (Dordrecht: Reidel), p. 289.
Lupie, O. L., and Nordsieck, K. H. 1987, *A.J.*, **92**, 214.
Maeder, A. 1981, in *Proc. ESO Workshop on The Most Massive Stars*, ed. S. D'Odorico, D. Baade, and K. Kjär (Garching: ESO) p. 173.
Massey, P. 1980, *Ap. J.*, **236**, 526.
———. 1981, *Ap. J.*, **246**, 153.
Massey, P., and Conti, P. S. 1981*a*, *Ap. J.*, **244**, 169.
———. 1981*b*, *Ap. J.*, **244**, 173.
Massey, P., Lundström, I., and Stenholm, B. 1984, *Pub. A.S.P.*, **96**, 618.
McLean, I. S. 1980, *Ap. J.* (*Letters*), **236**, L149.
Moffat, A. F. J., Lamontagne, R., and Cerruti, M. A. 1986, *Pub. A.S.P.*, **98**, 1170.
Moffat, A. F. J., Lamontagne, R., Shara, M. M., and McAlister, H. A. 1986, *A.J.*, **91**, 1392.
Moffat, A. F. J., and Seggewiss, W. 1987, *Messenger*, **49**, 26.
Moffat, A. F. J., and Shara, M. M. 1986, *A.J.*, **92**, 952.
Plavec, M. 1968, *Adv. Astr. Ap.*, **6**, 202.
Proetel, K. 1978, Thesis, Ruprecht-Karls-Universität Heidelberg.
Rudy, R. J., and Kemp, J. C. 1978, *Ap. J.*, **221**, 200.
Robert, C., Drissen, L., St.-Louis, N., Moffat, A. J. F., and Bastien, P. 1988, in preparation.
Schmidt, G. D. 1988, in *Polarized Radiation of Circumstellar Origin, Proc. Vatican Conference on Circumstellar Polarization*, ed. G. Coyne *et al.* in press.
Schmutz, W., Hamann, W.-R., and Wesselowski, U. 1988, *Astr. Ap.*, in press.
Schulz, A. 1980, Thesis, Ruprecht-Karls-Universität Heidelberg.
Serkowski, K. 1974, in *Methods of Experimental Physics* **12**, Astrophysics, Part A.
Serkowski, K., Mathewson, D. S., and Ford, V. L. 1975, *Ap. J.*, **196**, 261.
Smith, L. F., and Hummer, D. G. 1988, *M.N.R.A.S.*, **230**, 511.
St.-Louis, N., Drissen, L., Moffat, A. F. J., and Bastien, P. 1987, *Ap. J.*, **322**, 870.
St.-Louis, N., Moffat, A. F. J., Drissen, L., Bastien, P., and Robert, C. 1988, *Ap. J.*, **330**, 286.
Torres, A. V. 1988, *Ap. J.*, **325**, 795.
Torres, A. V., Conti, P. S., and Massey, P. 1986, *Ap. J.*, **300**, 379.
van den Heuvel, E. P. J. 1976, in *IAU Symposium 73, Structure and Evolutions of Close Binary Systems*, ed. P. Eggleton, S. Mitton, and J. Whelan (Dordrecht; Reidel), p. 35.
van der Hucht, K. A., Cassinelli, J. P., and Williams, P. M. 1986*a*, *Astr. Ap.*, **168**, 111.
———. 1986*b*, *Astr. Ap.*, **175**, 356.
van der Hucht, K. A., Conti, P. S., Lundström, I., and Stenholm, B. 1981, *Space Sci. Rev.*, **28**, 227.
van der Hucht, K. A., Conti, P. S., and Willis, A. J. 1982, in *IAU Symposium Number 99, Wolf-Rayet Stars: Observations, Physics, Evolution*, ed. C. W. H. de Loore and A. J. Willis, (Dordrecht: Reidel), p. 277.
van der Hucht, K. A., Hidayat, B., Admiranto, A. G., Supelli, K. R., and Doom, C. 1988, *Astr. Ap.*, **199**, 217.
Weller, W. G., and Jeffers, S. 1979, in *IAU Symposium Number 83, Mass Loss and Evolution of O-type Stars*, ed. P. S. Conti and C. W. H. de Loore (Dordrecht: Reidel), p. 27.
Williams, P. M., van der Hucht, K. A., and Thé, P. S. 1987*a*, *Astr. Ap.*, **182**, 91.
———. 1987*b*, *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., van der Hucht, K. A., Conti, P. S., and Garmany, C. D. 1986, *Astr. Ap. Suppl.*, **63**, 417.
Wilson, O. C. 1940, *Pub. A.S.P.*, **52**, 404.

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