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POLARIZATION VARIABILITY AMONG WOLF-RAYET STARS. VII. THE SINGLE STARS WR 14, WR 25, AND WR 69

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ABSTRACT

We have monitored over an interval of 1 month the linear polarization in visible light of three single Wolf-Rayet stars, WR 14 (WC6), WR 25 (WN7), and WR 69 (WC9). As for other early-type WC stars, WR 14 is not significantly variable (at the $\sigma \sim 0.03\%$ level) during this set of observations; however, its mean polarization level is significantly different from its value in 1987. The two other stars do vary ($\sigma \sim 0.06\%$) as expected for late-type W-R stars of either sequence. The high value of $P_{max}/E_{B-V} \geq 11$ for WR 25 suggests an extremely high efficiency of grain alignment in the line of sight to the star. The wavelength dependency of the polarization angle, as well as long-term variability in the U band, suggest some intrinsic polarization component as well for this star.

Subject headings: circumstellar matter — polarization — stars: mass-loss — stars: Wolf-Rayet

1. INTRODUCTION

Study of the polarization variability among early-type stars is a very powerful tool. In the case of binary systems with sufficient circumstellar scattering material, phase-locked variations are used to determine some basic parameters, such as the inclination of the orbit, the distribution of the scattering material around the stars, and the rate of mass loss (St.-Louis et al. 1988). For single stars, polarization changes are generally taken as the signature of inhomogeneities or asymmetries in the wind. In 1984, we started to monitor systematically a large number of Wolf-Rayet (W-R) stars. The main result that emerged from the study of the single stars is an anticorrelation between the amplitude of the random polarization variations and the terminal wind speed: late-type WN8 and WC9 stars tend to be highly variable ($\Delta P \sim 0.4\%$–0.8%), while the hotter subtypes show little or no variability above the instrumental scatter (e.g., for WC5–7: $\Delta P \leq 0.05\%$) (Drissen et al. 1987; Robert et al. 1989). It has been argued that the photometric, polarimetric, and spectroscopic variations observed in W-R stars have a common origin, namely stochastic instabilities in the wind (Moffat & Robert 1991).

We present here new observations of two single WC stars, HD 76536 (WR 14, WC6) and HD 136488 (WR 69, WC9), as well as a known polarimetrically variable WN7 star in Carina, HD 93162 (WR 25). The first two stars provide a natural extension of previous monitoring of bright stars, while the third star is known to show unusual properties.

2. OBSERVATIONS

The observations were carried out with the MINIPOL polarimeter attached to the University of Toronto 60 cm telescope at Las Campanas, Chile, in 1990 February–March. The bulk of the observations was obtained with a wide-band blue filter as used before ($\lambda_c = 4700$ Å, FWHM = 1800 Å). The internal calibration system of the instrument allows us to derive with high accuracy the polarization efficiency and the origin of the polarization angle without relying too much on polarized standards (see Dolan & Tapia 1986 for a description of the calibration system of the MINIPOL). The standard stars HD 110984, HD 147084, and HD 126593 (Tapia 1988) were nevertheless regularly observed; their observed value of P and Θ agreed, within the uncertainties, with their expected value. The instrumental polarization, determined by observations of two unpolarized standard stars, 61 Vir and HD 100623, was found to be negligible ($P_{inst} \leq 0.015\%$).

The data, presented in Tables 1 (WR 14), 2 (WR 25), and 3 (WR 69), are plotted against Julian date in Figure 1. In the tables, column (1) refers to the Julian date of the observation; columns (2) and (3) to the degree of linear polarization P and its mean error, σ_P; and column (4) to the position angle, θ, in the equatorial system.

3. RESULTS AND DISCUSSION

3.1. *WR 14 and WR 69*

As one can see from Figure 1, variations in P and θ of WR 14 are barely significant. To quantify the variations, we can compare the values of σ_1^2 (corresponding to the expected mean instrumental variance) and σ_2^2 (the observed variance of the data; i.e., how much scatter there is from the mean), as defined by Bastien et al. (1988):

$$\sigma_1^2(P) = N\left(\sum_{i=1}^{N} \frac{1}{\sigma_i^2}\right)^{-1}$$

$$\sigma_2^2(P) = \frac{[\Sigma_{i=1}^N(Q_i - \bar{Q})^2 + \Sigma_{i=1}^N(U_i - \bar{U})^2]}{2(N-1)},$$

where $Q_i = P_i \cos(2\theta_i)$, $U_i = P_i \sin(2\theta_i)$, $\bar{Q}$ and $\bar{U}$ are the unweighted averages, and σ_i are the errors of the individual data points (see also Bastien 1982).

For WR 14, $\sigma_2 = 0.036\% = 1.5\ \sigma_1$, and thus the observed variations are of statistically low significance (see Bastien et al. 1988). This agrees well with other hot WC stars observed pre-

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TABLE 1

POLARIMETRIC OBSERVATIONS OF WR 14

Julian Date (2,447,000+) (1)	P(%) (2)	σ_p(%) (3)	θ (4)
929.640.........	2.751	0.025	169°6
930.601.........	2.656	0.035	169.2
931.598.........	2.675	0.030	168.8
932.596.........	2.644	0.021	169.4
933.601.........	2.709	0.027	169.2
934.604.........	2.710	0.018	169.5
935.597.........	2.683	0.019	169.1
937.599.........	2.690	0.020	169.3
938.679.........	2.722	0.016	169.3
939.608.........	2.729	0.023	168.8
940.820.........	2.680	0.020	170.4
941.583.........	2.668	0.019	169.3
942.610.........	2.688	0.025	168.8
943.552.........	2.674	0.028	169.2
944.587.........	2.731	0.018	168.6
945.590.........	2.685	0.023	168.8
947.590.........	2.644	0.018	168.6
948.585.........	2.695	0.028	169.0
949.590.........	2.677	0.025	168.4
951.688.........	2.643	0.039	169.5
952.600.........	2.678	0.032	168.5
967.582.........	2.699	0.011	169.5
968.565.........	2.686	0.026	169.3
969.560.........	2.728	0.021	169.0
970.553.........	2.652	0.024	169.0
971.563.........	2.719	0.028	169.5
972.566.........	2.710	0.019	169.5

viously (Robert et al. 1989) which do not show variations above the instrumental level. Robert & Moffat (1989) reported an average value of $P = 2.85\% \pm 0.02\%$ and $\theta = 170\fdg6 \pm 0\fdg2$ for WR 14 in 1988 February. This value, based on two data points obtained 2 weeks apart with the same broad-band blue filter as the data presented here, is significantly different within the formal errors from the 1990 average ($P = 2.69\% \pm 0.005\%$ and $\theta = 169\fdg2 \pm 0\fdg2$). Although the difference in polarization angle can easily be accounted for by different instrument settings not allowed for here and normally of the order of 1°, the difference in the length of the polarization vector, $\Delta P = 0.16\%$, is intriguing. A possible explanation is that WR 14 may be a long-period binary system in an eccentric orbit. Observations of the 78 day system γ^2 Vel (WC8 + O9 I, $e = 0.4$; St.-Louis et al. 1987) and the 113 day binary WR 133 (Robert et al. 1989; Moffat 1991) have shown that the polarization remains fairly constant during most of the orbit but changes rapidly (with an amplitude of $\sim 0.2\%$ around periastron). However, the spectrum of WR 14 shows no evidence for such a companion (van der Hucht et al. 1988). WR 14 might also exhibit some slowly varying intrinsic polarization caused by an asymmetric envelope. This star may deserve further long-term monitoring.

In the case of WR 69, $\sigma_2 = 0.056\% = 2.2\,\sigma_1$ implying significant variability. No obvious periodicity was detected with a period-search routine similar to that of Deeming (1975). Although WR 69 is the most variable of the three stars presented here, it is more stable than the other sole WC9 star for which extended data bases are available, HD 164270 (WR 103): $\sigma_2 = 0.067\% = 3.5\sigma_1$ (St.-Louis et al. 1987; see also Schulte-Ladbeck & van der Hucht 1989).

TABLE 2

POLARIMETRIC OBSERVATIONS OF WR 25

Julian Date (2,447,000+) (1)	P(%) (2)	σ_P(%) (3)	θ (4)
930.632.........	6.258	0.026	135°1
931.632.........	6.257	0.021	135.0
932.619.........	6.229	0.022	135.0
934.621.........	6.268	0.021	135.1
935.663.........	6.279	0.019	135.0
937.670.........	6.262	0.022	134.8
939.730.........	6.226	0.022	134.6
940.760.........	6.267	0.016	134.6
941.625.........	6.342	0.020	134.9
943.661.........	6.244	0.018	135.2
945.674.........	6.259	0.019	134.6
946.653.........	6.263	0.022	134.6
948.653.........	6.244	0.018	134.9
950.688.........	6.258	0.022	134.6
951.701.........	6.252	0.019	134.5
952.690.........	6.274	0.017	134.7
967.652.........	6.206	0.018	135.6
968.674.........	6.245	0.030	134.9
969.646.........	6.206	0.024	135.1
970.640.........	6.306	0.020	135.1
971.650.........	6.306	0.018	134.9
972.615.........	6.290	0.016	135.0

TABLE 3

POLARIMETRIC OBSERVATIONS OF WR 69

Julian Date (2,447,000+) (1)	P(%) (2)	σ_P(%) (3)	θ (4)
927.866.........	2.714	0.029	61°0
928.845.........	2.629	0.037	61.9
929.840.........	2.727	0.035	61.4
930.870.........	2.619	0.033	62.3
931.875.........	2.756	0.029	61.7
934.875.........	2.680	0.026	60.8
935.872.........	2.687	0.020	61.2
937.856.........	2.579	0.016	62.1
938.874.........	2.684	0.019	63.2
940.860.........	2.618	0.025	61.7
942.877.........	2.553	0.030	61.8
943.869.........	2.624	0.024	61.4
944.865.........	2.631	0.033	61.5
945.872.........	2.626	0.019	62.7
946.875.........	2.648	0.016	62.4
947.878.........	2.659	0.020	61.1
948.870.........	2.690	0.019	61.4
949.875.........	2.737	0.020	61.3
950.869.........	2.696	0.025	62.3
951.873.........	2.663	0.025	61.8
952.875.........	2.691	0.021	61.4
967.855.........	2.609	0.028	63.1
968.840.........	2.649	0.019	62.4
969.845.........	2.636	0.027	62.2
970.850.........	2.632	0.028	61.7
971.866.........	2.562	0.022	62.0
972.845.........	2.653	0.021	62.9

3.2. *WR 25*

WR 25 was already monitored in polarization in 1986 (Drissen et al. 1987), but two factors prompted us to observe it again. First, the variations seemed to occur in a preferred plane: this is rather unusual for a single W-R star, and suggested either that the star was in a long-period binary system or that its envelope was somewhat flattened. Second, the wavelength dependence of the observed polarization did not fit the interstellar law well, suggesting an intrinsic component of unknown source.

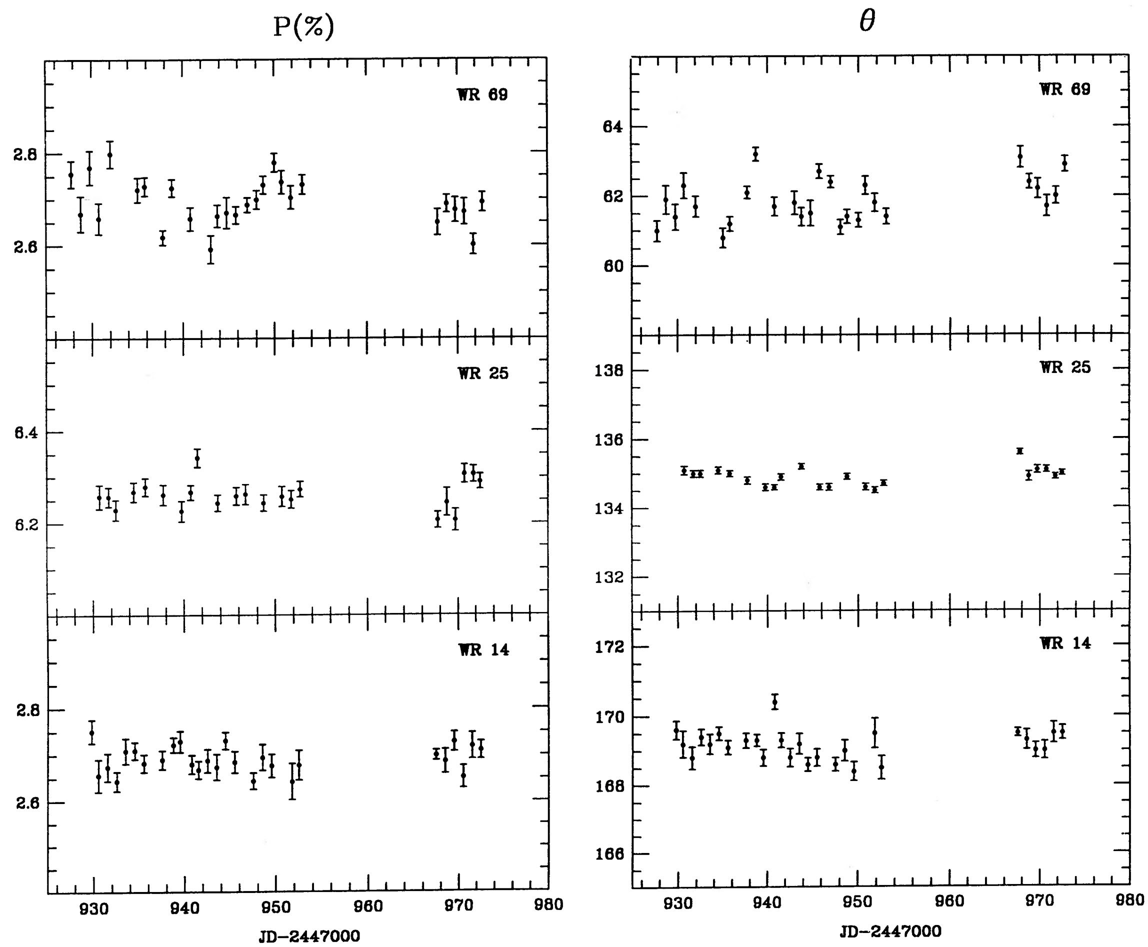

FIG. 1.—Polarization amplitude (P) (*left*) and position angle (θ) (*right*) as a function of Julian date for WR 14 (HD 76536), WR 25 (HD 93162), and WR 69 (HD 136488). Error bars refer to 2 σ estimates.

Turning to the new observations, Figure 2 shows the variations of WR 25 in the (Q, U)-plane. No privileged direction in the variations is obvious, contrary to what was seen in 1986.

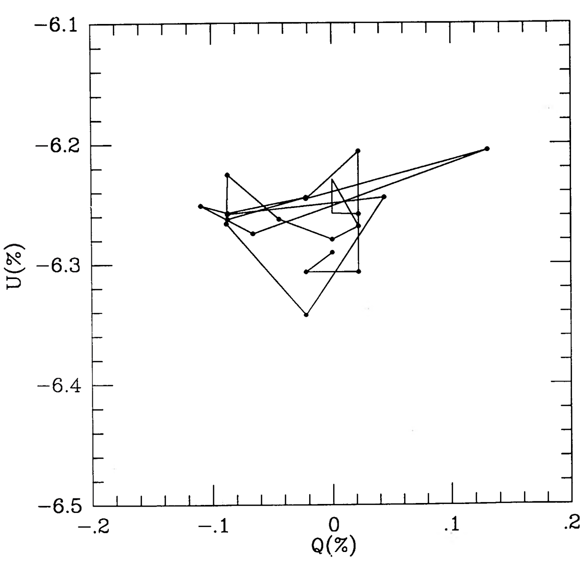

FIG. 2.—Polarimetric variations for WR 25 in the (Q, U)-plane.

Schulte-Ladbeck & van der Hucht (1989) have also observed that the polarization variations of WR 103 (WC9) occurred in a preferred plane, while St.-Louis et al. (1987) found no evidence of such a behavior in their data. Possibly, the asymmetries responsible for the polarization variations appear intermittently during a few days or even weeks predominantly at a certain location within the wind. It remains to be seen whether this behavior is random or not on a long time scale.

Figure 3 shows the wavelength dependence of the polarization (see Table 4). These data (obtained on 1990 July 25) were fitted to the empirical interstellar polarization law (Serkowski, Mathewson, & Ford 1975):

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

where $K = 1.15$. As some can see, the fit is in excellent agreement with the observations (giving $\lambda_{\max} = 6050 \pm 10$ Å and $P_{\max} = 6.73\% \pm 0.01\%$). The best fit obtained using the revised interstellar polarization law (with $K = 1.86\lambda_{\max} - 0.1$; Wilking, Lebofsky, & Rieke 1982) gave a similar result ($\lambda_{\max} = 6170 \pm 15$ Å and $P_{\max} = 6.74\% \pm 0.02\%$) but with slightly higher residuals. This suggests that the polarization observed for W-R 25 is completely interstellar. However, as it is shown in Figure 4, the data at different wavelengths do not fall on a straight line in the (Q, U)-plane. This behavior indicates a variation of the position angle as a function of wavelength. Two possible explanations can account for this phenomenon.

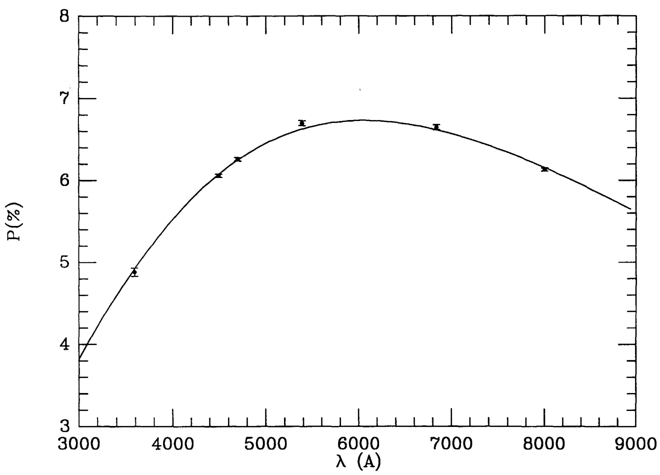

FIG. 3.—Polarization as a function of wavelength for WR 25. The solid line represents a fit to the interstellar polarization law (see text) with $P_{max} = 6.73\%$ and $\lambda_{max} = 6050$ Å.

a. The interstellar polarization angle is wavelength-dependent.—This phenomenon is observed in $\sim 13\%$ of the stars for which the polarization is predominantly interstellar (although an intrinsic component is also suspected for many of them; Coyne 1974), and occurs when the starlight traverses regions having different dust grain sizes and orientation. In this case, however, one should expect a rather low polarization efficiency, measured by the ratio of polarization to interstellar reddening, P_{max}/E_{B-V}. The value of P_{max}/E_{B-V} for WR 25 is very high: assuming $A_V = 1.53$ from Conti & Vacca (1990) and $R_V \equiv A_V/E_{B-V} = 5.6\lambda_{max}$ (μm) (from Whittet & van Breda 1978) = 3.4, we get $P_{max}/E_{B-V} = 15.0$, which is far above the empirical limit of 9.0 obtained from observation of 180 stars by Serkowski et al. (1975; see also Clayton & Cardelli 1988). Using the value given by Schmutz & Vacca (1991), $E_{B-V} = 0.61$, yields $P_{max}/E_{B-V} = 11.0$, which is still very high. Such a high value, if completely interstellar, is caused by a very high efficiency of grain alignment by the interstellar magnetic field. Another WR star in the Carina nebula, HD 93131 (WR 24), also has a high value of P_{max}/E_{B-V}: using $P_{max} = 2.35\%$ from Drissen et al. (1987) and $E_{B-V} = 0.20$ from Schmutz & Vacca (1991) yields $P_{max}/E_{B-V} = 11.8$. Tapia et al. (1988) present evidence for anomalous extinction in some parts of the Carina nebula. According to these authors (see also Aiello et al. 1988).

TABLE 4

MULTICOLOR POLARIMETRY OF WR 25

Filter	λ_c(Å)	FWHM(Å)	P(%)	σ_P(%)	θ
		1990			
U	3591	370	4.88	0.04	132°3
B	4494	735	6.06	0.02	134.3
4700	4700	1800	6.26	0.02	135.0
G	5388	700	6.70	0.03	135.4
R	6838	670	6.65	0.03	136.8
I	7998	620	6.13	0.02	137.1
		1986[a]			
U	3591	370	5.58	0.06	133°3
4700	4700	1800	6.33	0.02	133.7
I	7998	620	6.21	0.02	136.1

[a] From Drissen et al. 1987.

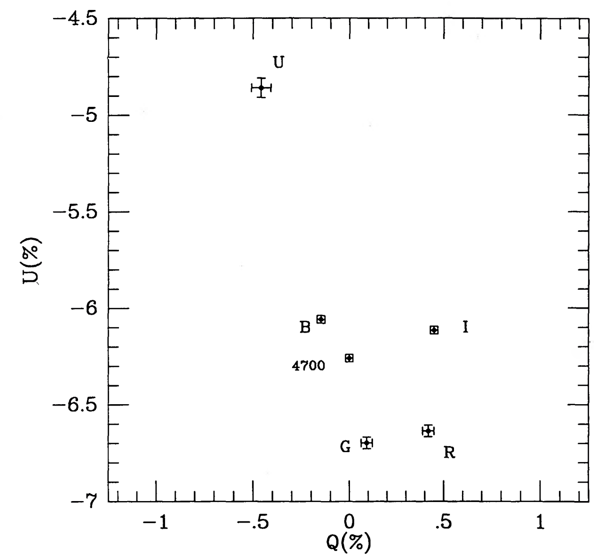

FIG. 4.—Wavelength dependence of the polarization in the (Q, U)-plane for WR 25.

processing of interstellar grains by shock waves inside the nebular complex may substantially reduce the $B-V$ excess per unit column density compared to the general interstellar medium, thus explaining the high value of P_{max}/E_{B-V} observed for WR 24 and WR 25. The wavelength dependence of the polarization angle could also be a result of the peculiar grain characteristics. A systematic study of the interstellar polarization in the direction of the Carina nebula might prove interesting.

b. An intrinsic polarization component, with a wavelength-dependent intensity and/or position angle, is present.—The shape of the curve in Figure 3 indicates that the intrinsic component, if any, is small compared to the interstellar component. However, the presence of an intrinsic component, which was previously suspected (Drissen et al. 1987), is strengthened by the observation of a large difference in the U filter data between 1986 and 1990: although the average polarization in the 4700/1800 and I filters are similar in 1990 as they were in 1986, the U polarization decreased from 5.6% to 4.9%. Regular observation of unpolarized standard stars in the U band with and without a Glan prism rule out an instrumental effect in this case. Could this be a binary-induced variation? Photometry and spectroscopy by Moffat (1978) argue against this possibility, unless one assumes a very low inclination or long period for the orbit. Pollock (1991), however, suggests that the very high X-ray luminosity of WR 25 (L_X[0.4–4.0 keV] = 4.2×10^{33} ergs s^{-1}), which is two orders of magnitude greater than for typical single WR stars, may be caused by colliding winds in a binary system, as in the long-period WC7+O4 binary HD 193793 (WR 140). A polarization induced by pure electron scattering (as in the case of hot stars in a binary system) is expected to show constant intensity and position angle as a function of wavelength (McLean 1979), and thus the combined intrinsic plus interstellar polarization values in different filters should also lie on a straight line in the (Q, U)-diagram, which is not the case here. Nevertheless, the presence of shocks, along with a possible magnetic field, could induce the kind of wavelength dependence observed here. Taylor et al. (1991) reported that the intrinsic polarization of the hypergiant star P Cygni is also wavelength-dependent. Moreover, the slope of this dependence varies with time. Taylor et al. attribute this behavior to absorption effects within the stellar envelope. This effect is primarily seen in Be stars, where the Balmer jump is prominent (Coyne & McLean 1981). Although such a discontinuity is not conspicuous in WR 25 (Schmutz & Vacca 1991), absorption effects cannot be ruled out (in fact, all Balmer lines are in absorption in WR 25; see Moffat 1978).

4. SUMMARY

We have presented polarimetric data for three apparently single WR stars. The short-term behavior of the stars is comparable to that of other WR stars of similar subtype: the WC6 star WR 14 shows no variations above the instrumental scatter, while WR 69 (WC9) and WR 25 (WN7) are more variable. In the last two cases, the variations appear at random times and can be interpreted as stochastic instabilities in the wind. The long-term variability of WR 25, as well as the wavelength dependence of its polarization angle, are more puzzling. They may be caused by a variable global asymmetry of its stellar envelope combined with absorption effects not taken into account in the pure electron scattering-induced polarization model. This star would be an interesting target for spectropolarimetry. The high value of the ratio of polarization to interstellar reddening for WR 25, as well as for the nearby WN7 star WR 24, indicate a very high efficiency of grain alignment by the interstellar magnetic field in the direction of the Carina nebula. Further investigation of the interstellar polarization in this direction might be interesting.

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