AN EXTREME CASE OF A MISALIGNED HIGHLY FLATTENED WIND IN THE WOLF-RAYET BINARY CX CEPHEI

A. Villar-Sbaffi,1 N. St-Louis,1 Anthony F. J. Moffat,1 and Vilppu Piirola2,3

Abstract

CX Cep (WR 151) is the WR+O binary (WN5+O5 V) with the second shortest period known in our Galaxy. To examine the circumstellar matter distribution and to better constrain the orbital parameters and mass-loss rate of the W-R star, we obtained broadband and multiband (i.e., UBVRI) linear polarization observations of the system. Our analysis of the phase-locked polarimetric modulation confirms the high orbital inclination of the system (i.e., $i = 65^\circ$). Using the orbital solution of Lewis et al. (1993), we obtain masses of 33.9 and 23.9 $M_\odot$ for the O and W-R stars, respectively, which agree with their spectral types. A simple polarimetric model accounting for finite stellar size effects allowed us to derive a mass-loss rate for the W-R star of $(0.3 \pm 0.5) \times 10^{-5} M_\odot \, \text{yr}^{-1}$. This result was remarkably independent of the model’s input parameters and favors an earlier spectral type for the W-R component (i.e., WN4). Finally, using our multiband observations, we fitted and subtracted from our data the interstellar polarization. The resulting constant intrinsic polarization of $3\%-4\%$ is misaligned in relation to the orbital plane (i.e., $f_{\text{CIP}} = 26^\circ$ vs. $\Omega = 75^\circ$) and is the highest intrinsic polarization ever observed for a W-R star. This misalignment points toward a rotational (or magnetic) origin for the asymmetry and contradicts the most recent evolutionary models for massive stars (Meynet & Maeder 2003) that predict spherically symmetric winds during the W-R phase (i.e., CIP = 0%).

Subject headings: binaries: eclipsing — polarization — stars: individual (CX Cep) — stars: mass loss — stars: Wolf-Rayet — techniques: polarimetric

1. INTRODUCTION

Wolf-Rayet (W-R) stars have always puzzled astronomers in their attempt to explain their extreme mass loss and dense winds. Binarity was initially believed to be the only mechanism capable of expelling their outer layers, exposing their CNO-enriched cores, and producing their strong winds. However, the existence of single Wolf-Rayet stars with characteristics similar to those of their double-star counterparts was a big drawback for this scenario.

Radiative (line-driven) wind acceleration (Cassinelli & Castor 1973) is now the widely accepted explanation for the Wolf-Rayet phenomenon in massive stars. The strong UV radiation produced by massive stars coupled with significant metallicity provides a suitable environment for W-R-type winds to develop. The inclusion of rotation in massive star evolutionary models is now able to reconcile theoretical predictions with previously unexplained observational evidence (Meynet & Maeder 2000). For instance, the observed ratio of nitrogen-rich (WN-type) W-R stars to carbon-rich (WC-type) W-R stars is better reproduced by models that include rotation.

One important prediction of stellar evolution with rotation is that massive stars with solar or higher metallicities should reach the Wolf-Rayet phase with small rotational velocities even if their O-star progenitors rotate with speeds of up to 300 km s$^{-1}$ (Meynet & Maeder 2003). As massive stars age and lose their mass, most of their angular momentum is also carried away, and stars with the strongest winds (i.e., in high-metallicity environments) should be most affected by this spin-down process. Support for this prediction was provided by Harries et al. (1998) in their spectropolarimetric survey of a complete sample of northern W-R stars. These authors found no evidence for a high frequency of highly asymmetric envelopes around W-R stars, as would be the case for fast-rotating stars (Maeder 1999). Their conclusions were based on the rarity of emission-line depolarization in the spectra of the W-R stars surveyed. In fact, they found only three of 16 stars showing evidence of line depolarization at the 1 $\sigma$ level.

In this paper, we report on our high-precision linear polarimetric observations of the Galactic W-R binary CX Cep (WR 151) comprising an O5 V star and a nitrogen-rich WN5 star (Lewis et al. 1993). CX Cep has the second shortest period of all known WR+O systems in our Galaxy (i.e., P = 2.12 days), with very shallow photometric eclipses suggesting a relatively small orbital inclination (i.e., Lipunova & Chereshpashchuk [1982] found $i \approx 50^\circ$ based on the light-curve solution). Polarimetric observations by Kartasheva (2002b) and Schulte-Ladbeck & van der Hucht (1989) favor, however, a much higher inclination (i.e., $i \approx 70^\circ$–$80^\circ$ based on our reanalysis of their data; see § 3). Kartasheva (2002b) also noted large epoch-to-epoch fluctuations in both the degree of matter concentration toward the orbital plane and the polarimetric amplitude, similar to those observed for the 1.64 day W-R binary CQ Cep (Villar-Sbaffi et al. 2005; Kartasheva et al. 2000).

Our goals for this paper are to obtain a clearer picture of the matter distribution surrounding CX Cep using high-precision polarimetry with the highest time resolution possible. In § 2 we present our observations and method of reduction, followed by our broadband and multiband results in §§ 3 and 4, respectively. In § 5 we discuss the results and draw our final conclusions.

2. OBSERVATIONS AND REDUCTION

We used the 2.1 m telescope of the McDonald observatory equipped with a rotating Glan-prism polarimeter for our broadband multipoloch observations (see Breger 1979). To maximize
the photon count rate and because wavelength-independent Thomson scattering is the main polarizing mechanism in the winds from massive stars, our observations were carried out without a filter using a Hamamatsu R943A-02 photomultiplier with extended red response. Each integration lasted approximately 30 minutes and included observations of the moonlit sky to subtract background polarization. We chose our integration times in order to maintain the accuracy based on photon statistics\(^4\) close to 0.03% in both Stokes parameters \(Q\) and \(U\).

Our five-band observations were carried out at the 2.5 m Nordic Optical Telescope in the Canary Islands using the TURPOL photopolarimeter (Piirola 1988) equipped with a rotating achromatic half-wave plate for linear polarimetry. This instrument allowed us to obtain simultaneous polarimetric observations in the \(UBVRI\) bands by using a combination of filters and dichroics resulting in effective wavelengths of 360, 440, 530, 690, and 830 nm for each band, respectively. The integration times were chosen such that the accuracy based on the least-squares fit to the eight positions of the half-wave plate was less than 0.06% in the \(B\) band and the total integration time was less than 60 minutes. Sky background polarization was automatically subtracted using a plane-parallel calcite plate as the polarizing beam splitter (Piirola 1988). A summary of our observations is presented in Table 1.

For both sites we chose the standard polarized star HD 204827 (Hsu & Breger 1982) to calibrate the position angle. This well-documented standard remained constant, within \(\sim 1\degree\), throughout our runs and provided a reliable calibration. For our McDonald observations, HD 154345 (Gehrels 1974), HD 9407 (Gliese 1969), and HD 212311 (Schmidt et al. 1992) were used as standard unpolarized stars to determine the instrumental polarization. Numerous observations each night allowed us to determine an average value for the instrumental polarization in the Stokes parameters \(Q\) and \(U\), which was then subtracted from our data.

\(^4\) The accuracy based on photon statistics alone (i.e., Poisson statistics) should be regarded as a lower limit. Bastien (1982) showed that a more accurate estimate of the actual error can be found by multiplying this value by 1.5 in accordance with the spurious variability of standard polarized stars.

According to the operating manual of the TURPOL polarimeter at the Nordic Optical Telescope (NOT), the instrumental polarization attributable to the optics can be considered negligible in all bands. This was confirmed to an accuracy (based on photon statistics) of \(\sim 0.03\%\) by our own observations of the unpolarized standards HD 154345 (Gehrels 1974), HD 9407 (Gliese 1969), and HD 67228 (Piirola 1977). Therefore, we did not subtract any instrumental polarization from our NOT observations. The details of all these calibration measurements are presented in Table 2.

Our observations were analyzed using the standard Brown et al. (1978, hereafter BME78) Fourier method, which assumes an optically thin, corotating matter distribution with point sources, in order to determine the orbital parameters and the shape (i.e., moments) of the matter distribution. Accordingly, we represented the phase-locked variability of the Stokes parameters \(Q\) and \(U\) by fitting to our data (using \(\chi^2\) minimization) a Fourier expansion up to second harmonics:

\[
U(\phi) = U_0 + U_1 \cos \lambda + U_2 \cos 2\lambda + U_3 \sin \lambda + U_4 \sin 2\lambda,
\]

\[
Q(\phi) = Q_0 + Q_1 \cos \lambda + Q_2 \sin \lambda + Q_3 \cos 2\lambda + Q_4 \sin 2\lambda,
\]

where \(\lambda = 2\pi\phi\) and the light-curve phase \(\phi\) was calculated using the ephemeris for primary minimum (i.e., W-R star in front at phase 0.0) of Kurochkin (1985):

\[
\text{HJD}_{\text{min}} = 2444451.423 + 2.126897E.
\]

Although we expect W-R binaries like CX Cep to increase their orbital period as they lose mass through stellar winds (see, e.g., the case of V444 Cyg in St-Louis et al. 1993), \(\dot{P}\) in these systems is usually less than 0.1 s yr\(^{-1}\) and can be neglected.

From the coefficients of this Fourier expansion, we calculated the orbital inclination \(i\) and the orientation of the line of nodes \(\Omega\) according to the BME78 prescriptions. Our definition for the orientation of the line of nodes comes from Harries & Howarth.

| Parameter | McDonald 1 (2000) | McDonald 2 (2001) | McDonald 3 (2002) |
|-----------|------------------|------------------|------------------|
| Observatory | McDonald | NOT | McDonald | McDonald |
| Telescope size (m) | 2.1 | 2.5 | 2.1 | 2.1 |
| Instrument | Breger polarimeter | TURPOL | Breger polarimeter | Breger polarimeter |
| Filters | None | UBVRI | None | None |
| First night (UT) | Aug 31 | Oct 8 | Aug 30 | Sep 10 |
| Number of nights | 14 | 20 | 14 | 14 |

| Parameter | McDonald 1 (2000) | McDonald 2 (2001) | McDonald 3 (2002) |
|-----------|------------------|------------------|------------------|
| Observatory | McDonald | NOT | McDonald | McDonald |
| Telescope size (m) | 2.1 | 2.5 | 2.1 | 2.1 |
| Instrument | Breger polarimeter | TURPOL | Breger polarimeter | Breger polarimeter |
| Filters | None | UBVRI | None | None |
| First night (UT) | Aug 31 | Oct 8 | Aug 30 | Sep 10 |
| Number of nights | 14 | 20 | 14 | 14 |

\(a\) These values represent the average observed polarization of the assumed unpolarized stars HD 154345 (Gehrels 1974), HD 9407 (Gliese 1969), and HD 212311 (Schmidt et al. 1992) for our McDonald (unfiltered) observations and HD 154345 (Gehrels 1974), HD 9407 (Gliese 1969) and HD 67228 (Piirola 1977) for our NOT observations.

\(b\) HD 204827 was chosen as our standard polarized star for both sites with \(\theta_{\text{publ}} = 59\degree 3\) according to Hsu & Breger (1982).
in which \( \Omega \) represents the angle of the ascending node measured from north through east with the constraint \( \Omega < 180^\circ \) (i.e., an ambiguity of \( 180^\circ \) exists in the determination of \( \Omega \) since it is impossible from polarimetry to discern the ascending from the descending node). This definition differs from the one used by other authors, where \( \Omega_{QU} \) represents the orientation of the major axis of the ellipse traced in the \( QU \) plane. Finally, the \( \gamma_i \) moments of the matter distribution (see BME78) allowed us to calculate \( r_o G \) and \( r_o H \), describing, respectively, the degree of asymmetry about the orbital plane and the effective concentration of matter toward the orbital plane.

The errors on the parameters were determined using a Monte Carlo method by adding Gaussian noise to our data using the Poisson error associated with each point multiplied by a factor of 1.55 as the standard deviation of the distribution. In this manner, we generated 1000 synthetic data sets and evaluated the orbital parameters for each set using the same Fourier method described above. We defined our error on a particular parameter as the interval for which 95% (i.e., 2 \( \sigma \)) of our synthetic data sets could be found.

Because CX Cep has a small orbital separation (i.e., \( a \sim 25 R_\odot \); Lewis et al. 1993) and shows photometric eclipses, the system is expected to depart from the point-source approximation of BME78. Fox (1994) showed that a complete model for the polarimetric eclipses must take into account the reduction of direct unpolarized light during eclipses, the occultation of the shadowed regions behind the stars, and the nonuniform illumination of electrons located close to the stars. Drissen et al. (1986) developed a first-order correction for the reduction of the direct unpolarized light during eclipses that they successfully used to correct for the phase-locked light-curve variability in the short-period W-R binary CQ Cep (see also Villar-Sbaffi et al. 2005). However, because CX Cep’s light curve shows only small fluctuations in intensity (i.e., 0.13 and 0.04 mag dips at primary and secondary eclipses, respectively), we neglected this correction in our analysis. A detailed discussion on the departures from the BME78 point-source approximation will be presented later in this paper.

3. THE POLARIMETRIC ORBIT

The goals of our broadband (Texas) observations of CX Cep were to obtain the most precise polarimetric orbit possible and study the epoch-to-epoch and non-BME78 polarimetric variability of the system. Unfortunately, highly variable atmospheric conditions coupled with the presence of the moon on our last two missions (i.e., 2001 and 2002) affected the reliability of our polarimetric measurements of this relatively faint system (\( V = 12.5 \) mag). This resulted in noisier, less reliable data sets with fewer measurements than our 2000 data. Our observations as a function of light-curve phase in the Stokes \( Q \) and \( U \) representation are shown in Figure 1.

3.1. BME78 Analysis

Using the BME78 diagnostics, we obtained the orbital parameters of CX Cep. The coefficients of our fit are presented in Table 3 along with the resulting orbital parameters. We also revisited the data of Kartasheva (2002b) and Schulte-Ladbeck &

---

**Fig. 1.—Normalized \( Q \) and \( U \) Stokes parameters for our unfiltered McDonald observations as a function of the 2.12 day light-curve phase of CX Cep. These observations were fitted separately for each epoch to a Fourier expansion up to second harmonics (solid line) following the prescriptions of BME78.**

---

5 We multiplied our Poisson errors by a factor of 1.5 in order to comply with the findings of Bastien (1982).
van der Hucht (1989) and applied the same method of reduction that we used for our own data. The errors on the polarimetric measurements by Kartasheva (2002b) are quoted as being in the range 0.1%–0.15% with no information regarding the errors on each single measurement. Therefore, for the purpose of this analysis, we assumed an error of 0.13% on each individual measurement. For Schulte-Ladbeck & van der Hucht (1989), we used the reprocessed data (corrected using the ephemeris of Kurochkin (2002a) and the original Poisson errors. The resulting parameters are presented in Table 3.

We note that these revised results are considerably different from those published originally. Kartasheva (2002a, 2002b) probably used a different set of errors (i.e., weights) from the ones as- sumed in this paper to perform the χ² minimization. This strong instability in the solutions is reflected by the high errors on the resulting orbital parameters. We also note that the large differences in the O₉ and U₀ constants between the Kartasheva (2002b) V-band observations and the other unfiltered (i.e., white-light) observations is easily explained by the wavelength dependence of the high interstellar polarization component (see § 4) that usually peaks in the V band.

Our multiepoch results for the orbital parameters agree (within 2σ) with each other and with the (revised) results from other authors, although our last two years are plagued by higher uncertainties due to the noisier data sets. Because the system had a more gradual eclipse by the O star of the dense inner regions of the W-R wind during secondary eclipse. This simple model allowed the authors to constrain the stellar radii of both stars along with the mass-loss rate and velocity law of the W-R star.

3.2. Phase-locked Non-BME78 Variability

Phase-locked non-BME78 variability in polarimetric data has already been found in a few W-R binaries (e.g., St-Louis et al. 1993; Villar-Sbaffi et al. 2005). In short-period binaries, the most important cause of BME78 departures is the violation of the point-source assumption due to the comparable size of the orbital separation and the stellar radii (e.g., a ∼ 25 Rₜ & R₀ ∼ 15 Rₜ for CX Cep).

In order to better appreciate these deviations from the predicted double-wave behavior in CX Cep, we binned our 2000 data (i.e., the most reliable data set) in phase intervals of 0.03. This binning allowed us to average out the stochastic polarimetric fluctuations caused by the presence of fast-moving blobs in the wind of the W-R star (see Robert et al. 1989). The effect of these blobs on the polarization should be maximal around phases 0.0 and 0.5 due to the alignment along the line of sight of the stars during eclipses. This is in agreement with the larger scatter observed in our data around those phases. Finally, we rotated the data by −ΩQU = 30° in the QU plane (see Table 3) to the orbital plane of symmetry of the system and plotted the polarization in Stokes Q and U as a function of light-curve phase (Fig. 2). A clear non-BME78 (i.e., non-double-wave) structure appears around phase 0.5 when the O star eclipses the W-R star. A similar structure has been observed in the W-R binaries V444 Cyg (St-Louis et al. 1993) and CQ Cep (Villar-Sbaffi et al. 2005). This non-BME78 modulation was successfully modeled for V444 Cyg by considering the effect of the gradual eclipse by the O star of the dense inner regions of the W-R wind during secondary eclipse. This simple model allowed the authors to constrain the stellar radii of both stars along with the mass-loss rate and velocity law of the W-R star.

### Table 3

Polarimetric Parameters of CX Cep from our Unfiltered Observations

| Parameter | Unfiltered Results (McDonald) | Schulte-Ladbeck & van der Hucht (1989) Unfiltered | Kartasheva (2002b) |
|-----------|--------------------------------|-----------------------------------------------|-------------------|
|           | 2000                           | 2001                           | 2002              |
| U₀ (%)    | 6.068 ± 0.002                  | 6.176 ± 0.004                  | 6.095 ± 0.001     |
| U₁ (%)    | -0.022 ± 0.002                 | -0.047 ± 0.007                 | 0.075 ± 0.006     |
| U₂ (%)    | -0.027 ± 0.003                 | -0.003 ± 0.003                 | 0.049 ± 0.010     |
| U₃ (%)    | 0.053 ± 0.002                  | 0.057 ± 0.006                  | -0.023 ± 0.006    |
| Q₀ (%)    | 0.182 ± 0.003                  | 0.196 ± 0.005                  | 0.185 ± 0.007     |
| Q₁ (%)    | -0.390 ± 0.002                 | -0.400 ± 0.004                 | -0.476 ± 0.007    |
| Q₂ (%)    | 0.006 ± 0.002                  | -0.162 ± 0.007                 | -0.034 ± 0.006    |
| Q₃ (%)    | -0.006 ± 0.002                 | 0.047 ± 0.003                  | -0.046 ± 0.010    |
| b (deg)   | 75 ± 1                         | 69 ± 2                         | 61 ± 6            |
| i (deg)   | 73 ± 2                         | 79 ± 3                         | 63 ± 20           |
| τ₉G (%)   | 0.018                          | 0.087                          | 0.053             |
| τ₉H (%)   | 0.250                          | 0.269                          | 0.165             |
| rmsₚ (%) | 0.059                          | 0.071                          | 0.065             |
| rmsₜ (%) | 0.075                          | 0.080                          | 0.077             |

* The errors on τ₉G and τ₉H were found to be less than 0.02% at the 2σ level, and we decided not to present them explicitly.

Our definition for Ω is that of Harries & Howarth (1996).

We also note that the large differences in the O₉ and U₀ constants between the Kartasheva (2002b) V-band observations and the other unfiltered (i.e., white-light) observations is easily explained by the wavelength dependence of the high interstellar polarization component (see § 4) that usually peaks in the V band.

### Table 3

Polarimetric Parameters of CX Cep from our Unfiltered Observations

| Parameter | Unfiltered Results (McDonald) | Schulte-Ladbeck & van der Hucht (1989) Unfiltered | Kartasheva (2002b) |
|-----------|--------------------------------|-----------------------------------------------|-------------------|
|           | 2000                           | 2001                           | 2002              |
| U₀ (%)    | 6.068 ± 0.002                  | 6.176 ± 0.004                  | 6.095 ± 0.001     |
| U₁ (%)    | -0.022 ± 0.002                 | -0.047 ± 0.007                 | 0.075 ± 0.006     |
| U₂ (%)    | -0.027 ± 0.003                 | -0.003 ± 0.003                 | 0.049 ± 0.010     |
| U₃ (%)    | 0.053 ± 0.002                  | 0.057 ± 0.006                  | -0.023 ± 0.006    |
| Q₀ (%)    | 0.182 ± 0.003                  | 0.196 ± 0.005                  | 0.185 ± 0.007     |
| Q₁ (%)    | -0.390 ± 0.002                 | -0.400 ± 0.004                 | -0.476 ± 0.007    |
| Q₂ (%)    | 0.006 ± 0.002                  | -0.162 ± 0.007                 | -0.034 ± 0.006    |
| Q₃ (%)    | -0.006 ± 0.002                 | 0.047 ± 0.003                  | -0.046 ± 0.010    |
| b (deg)   | 75 ± 1                         | 69 ± 2                         | 61 ± 6            |
| i (deg)   | 73 ± 2                         | 79 ± 3                         | 63 ± 20           |
| τ₉G (%)   | 0.018                          | 0.087                          | 0.053             |
| τ₉H (%)   | 0.250                          | 0.269                          | 0.165             |
| rmsₚ (%) | 0.059                          | 0.071                          | 0.065             |
| rmsₜ (%) | 0.075                          | 0.080                          | 0.077             |
from van der Hucht (2001). We assumed that the W-R wind consists exclusively of ionized helium and followed the prescriptions of Moffat & Marchenko (1993) to calculate the number of free electrons per nucleon in the wind for a typical WNE star. The radius of the O star was kept fixed at 11 $R_\odot$ using the most recent models of Martins et al. (2005) for an O5 V star. Although the spectral type of the O-star companion is still a source of debate (Kartasheva 2002a), our models were not very sensitive to changes in the O-star radius of $\pm 2 R_\odot$ (see Table 4).

We initially fixed the orbital inclination of our models at 73° based on the 2000 broadband results. However, we quickly realized that a lower inclination produced a much better fit to the binned data. An inclination of 65° was finally adopted. This value differs by $4\sigma$ from the one determined by the BME78 analysis. However, this discrepancy agrees with the results of Fox (1994), who showed that by considering occultation effects in the envelope of a modeled binary system, deviations of $\sim 3°$ could be found in the inclination derived by Fourier analysis of a synthetic polarimetric orbit.

The integrals were solved within a volume equal to 10 times the orbital separation by Monte Carlo integration using a Sobol quasi-random number sequence in three dimensions with a word length of 30 bits. The major improvement of our model was to replace the cutoff radius used by St-Louis et al. (1993) by the optical-depth $\tau$ along the line of sight, therefore replacing an arbitrary parameter (i.e., the cutoff radius) by a physical one. The cutoff radius was initially introduced in order to exclude high-density regions in the inner wind where multiple scattering leads to significant depolarization.

The optical depth for a scattered photon at coordinates $(x_0, y_0, z_0)$ was calculated by assuming that the only source of opacity was Thomson scattering:

$$
\tau = \int_{x_0}^{\infty} n_e(x, y, z_0) \sigma_T \, dx,
$$

where $\sigma_T = 6.65 \times 10^{-25}$ cm$^{-2}$ is the Thomson scattering cross section. The electron density $n_e(x, y, z)$ was determined using the principle of mass conservation at every point in the accelerated wind using a $\beta$-type velocity law with $\beta = 5$ and a sonic radius (i.e., $R_s$) of 2 $R_\odot$ for a typical WNE star. The high value of $\beta$ and the small sonic radius of the wind follow the optically thick radiation-driven wind models of Nugis & Lamers (2002), who were able to reproduce the high mass-loss rates of Wolf-Rayet stars. Here $\tau_{\text{max}} = 2/3$ was chosen as the maximum optical depth beyond which a photon became unpolarized and did not contribute to the total polarization. This optical depth corresponds to the adopted definition of a star’s photosphere and resulted in a good fit to the data (see models M10 and M11 in Table 4). However, because we assume that Thomson scattering is the only source of opacity and neglect line transitions, we are in fact underestimating the photospheric radius and overestimating its Thomson scattering optical depth (i.e., $\tau_{\text{max}}$). As

Table 4

| PARAMETER | M1 | M2 | M3 | M4 | M5 | M6 | M7 | M8 | M9 | M10 | M11 |
|-----------|----|----|----|----|----|----|----|----|----|-----|-----|
| $i$ (deg) | 65 | 60 | 70 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 |
| $\beta$ | 5 | 5 | 5 | 4 | 6 | 5 | 5 | 5 | 5 | 5 | 5 |
| $R_0$ ($R_\odot$) | 11 | 11 | 11 | 11 | 9 | 13 | 11 | 11 | 11 | 11 | 11 |
| $\tau_{\text{max}}$ | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.33 | 1.00 |
| $\Delta U$ (%) | 0.033 | 0.033 | 0.033 | 0.033 | 0.032 | 0.032 | 0.035 | 0.033 | 0.031 | 0.031 | 0.033 |
| $\Delta Q$ (%) | 4.96 | 4.96 | 4.95 | 4.96 | 4.95 | 4.96 | 4.97 | 4.95 | 4.95 | 4.95 |
| $\gamma$ (10$^{-17}$ $M_\odot$ km)$^{-1}$ | -3.74 | -3.70 | -3.77 | -3.74 | -3.75 | -3.73 | -3.74 | -3.76 | -3.72 | -3.72 | -3.73 |
| $M$ ($10^{-5}$ $M_\odot$ yr$^{-1}$)$^a$ | 6.1 | 5.4 | 6.6 | 6.6 | 5.6 | 5.5 | 6.9 | 8.4 | 4.9 | 9.3 | 4.8 |
| $\text{rms}$ (%)$^b$ | 0.13 | 0.29 | 0.36 | 0.36 | 0.30 | 0.30 | 0.37 | 0.45 | 0.27 | 0.50 | 0.26 |

$^a$ The mass-loss rate was determined assuming a typical terminal velocity (i.e., $V_\text{e}$) for the wind of a WN5 star of 1700 km s$^{-1}$.

$^b$ This $\text{rms}$ represents the average scatter of our binned data points from the modeled curve calculated by excluding any points in Stokes $Q$ located at $\pm 0.1$ in phase from the eclipses.
our models prove (see Table 4), a lower \( \tau_{\text{max}} \) results in a higher mass-loss rate for the W-R star. Therefore, the mass-loss rate determined with \( \tau_{\text{max}} = 2/3 \) represent a lower limit compared to the actual mass-loss rate.

In Figure 2 (solid line) and Table 4 (model M1) we present the best-fitting model to our binned data. The model was fitted by \( \chi^2 \) minimization by first determining the horizontal (i.e., \( \Delta \phi \)) and vertical (i.e., \( \Delta Q \) and \( \Delta U \)) offsets and finally by fitting the value \( \gamma = MV_V \), which controls simultaneously the amplitudes in Stokes \( Q \) and \( U \) (see St-Louis et al. 1993). Although our best fit is quite good, there are still a few structures in Stokes \( Q \) at phases 0.0 and 0.5 that could not be reproduced. These structures are probably signs of a complex matter distribution that might include a distorted wind-wind collision zone and a disklike density enhancement of the wind (see § 4). To avoid any problems caused by these structures on our final results, we excluded from the \( \chi^2 \) minimization any data points in Stokes \( Q \) located within \( \pm 0.1 \) phase around the eclipses.

Assuming a characteristic terminal velocity for a WNS wind of 1700 km s\(^{-1}\), we obtain a mass-loss rate for the W-R component of \( 0.3 \times 10^{-5} \, M_\odot \, \text{yr}^{-1} \). A few other models showing the effect of varying the orbital inclination (models M2 and M3), the exponent \( \beta \) of the velocity law (models M4 and M5), the star’s radii (models M6, M7, M8, and M9), and the maximum optical depth (models M10 and M11) are also shown in Table 4. Surprisingly, the mass-loss rate determined from all the models is remarkably stable and only fluctuates by about \( 0.2 \times 10^{-7} \, M_\odot \, \text{yr}^{-1} \) around the value determined from our best-fitting model. As we stated above, the adopted maximum Thomson scattering optical depth (i.e., \( \tau_{\text{max}} = 2/3 \) is our main source of uncertainty and, in fact, results in a lower limit for the mass-loss rate of the W-R star. However, because spectral lines only amount to approximately 10% of the total flux from a W-R star, we do not believe that \( \tau_{\text{max}} \) could be considerably lower than our assumed value of 2/3.

We also note that a small bias toward low mass-loss rates is inherent to our polarimetric model since we neglect the weaker O-star wind. In relation to W-R stars, O stars have lower mass-loss rates and faster winds and, therefore, lower densities in their circumstellar matter distribution. Since the fitted parameter \( \gamma \) (i.e., \( \gamma = MV_V \)) from which we derive the mass-loss rate is actually an average over the whole wind, the low-\( \gamma \) contribution from the O-star wind will decrease the mass-loss rate determined from our model. Fortunately, the matter distribution surrounding CX Cep is dominated by the strong W-R wind (see Lewis et al. 1993, their Fig. 14), and this bias is probably not very high.

Finally, on the basis of the resulting mass-loss rates from all our models, we believe that the mass-loss rate of the W-R star is in the range \( (0.3-0.5) \times 10^{-5} \, M_\odot \, \text{yr}^{-1} \), with a preference toward the higher value. A detailed two-wind model including wind-wind collision effects would certainly provide a more accurate result.

4. THE CONSTANT INTRINSIC POLARIZATION

By measuring the constant intrinsic polarization (CIP) of a star, we are in fact measuring the degree of spherical asymmetry of the matter distribution surrounding it. A high CIP implies a strong departure from spherical symmetry. In order to determine the CIP of a star, we must fit and remove the contribution of the interstellar polarization to the total observed polarization. For massive stars for which (wavelength-independent) Thomson scattering is the dominant source of linear polarization, this is usually done by obtaining multiwavelength (i.e., \( UBVRI \)) polarimetric observations of the star in order to subtract the wavelength-dependent interstellar contribution. Because in this section we are only interested in the CIP of the system, our multiband observations are scarcer in phase coverage and essentially serve to determine the zero point of the polarimetric variability in each band (see Fig. 3).

We note that a small wavelength-dependent intrinsic contribution to the polarization is expected due to the presence of strong emission lines in the spectrum of a W-R star (see, e.g., Moffat & Pirola 1993). These lines form far from the dense central regions of the wind, and their polarization can differ from that of the surrounding continuum (see Villar-Sbaffi et al. 2005). However, the line flux in a standard Johnson band only represents \( \sim 10\% \) of the total flux from the star, and we decided to neglect this effect in our analysis. The results of the BME78 analysis of the multiband observations are presented in Table 5.

The CIP of CX Cep was determined using the method described in Villar-Sbaffi et al. (2005). We assumed that the constant interstellar polarization could be represented by a modified Serkowski’s law (Serkowski et al. 1975):

\[
U_{\text{IS}}(\lambda) = P_{\text{max}} \sin(2\theta_{\text{IS}}) e^{-K(\lambda_{\text{max}})} \frac{\lambda^2}{\lambda^2_{\text{max}}},
\]

\[
Q_{\text{IS}}(\lambda) = P_{\text{max}} \cos(2\theta_{\text{IS}}) e^{-K(\lambda_{\text{max}})} \frac{\lambda^2}{\lambda^2_{\text{max}}},
\]

where \( P_{\text{max}} \) is the maximum interstellar polarization found at wavelength \( \lambda_{\text{max}} \). \( K(\lambda_{\text{max}}) = 0.01 + 1.66I(\lambda_{\text{max}}) \) (Whittet et al. 1992), and \( \theta_{\text{IS}}(\lambda) = C_1 + C_2/\lambda \) (Dolan & Tapia 1986; Moffat & Pirola 1993; Matsumura et al. 2003). The constant Stokes parameters \( Q_0 \) and \( U_0 \) from the BME78 analysis can then be expressed as

\[
U_0(\lambda) = U_{\text{WR}} - U_3 \frac{\sin^2 i}{1 + \cos^2 i} + U_{\text{IS}}(\lambda),
\]

\[
Q_0(\lambda) = Q_{\text{WR}} - Q_3 \frac{\sin^2 i}{1 + \cos^2 i} + Q_{\text{IS}}(\lambda),
\]

where \( U_{\text{WR}} \) and \( Q_{\text{WR}} \) are the components of the CIP vector from \( U_3 \), \( Q_3 \), and \( i \) were taken from our fit to the broadband 2000 data (see Table 3).

Using these equations and a nonlinear Levenberg-Marquardt code, we fitted simultaneously our values of \( Q_0 \) and \( U_0 \) to obtain the CIP of the system (i.e., \( Q_{\text{WR}} \) and \( U_{\text{WR}} \)) and the parameters describing the interstellar polarization (i.e., \( P_{\text{max}} \), \( \lambda_{\text{max}} \), \( C_1 \), and \( C_2 \)). The numerical weight of each band was taken to be the rms error on the double-wave fit to \( Q(\phi) \) and \( U(\phi) \) found in Table 5 and not the actual errors on \( Q_0 \) and \( U_0 \) determined from the fit. We justify this statement by the fact that the constants \( Q_0 \) and \( U_0 \) only represent the sum of the interstellar and intrinsic polarizations to the extent that the BME78 assumptions hold for this system. Therefore, we believe that the rms errors of the double-wave fit represent more accurately the relative weight to be given to each band. The resulting parameters for this first model (i.e., model 1) are presented in Table 6, and the fitted curve along with our data can be found in Figure 4.

Because of the possible instability of our solution due to the weak \( \lambda \)-dependency of the interstellar polarization, we performed another fit with the constraint \( Q_{\text{WR}} = U_{\text{WR}} = 0 \% \) to test the possibility that our first solution was statistically insignificant. The parameters of this second fit and the corresponding curve (i.e., model 2) can also be found in Table 6 and Figure 4.

With an rms error less than half that of model 2, model 1 provides a much better fit to the constant polarization of CX Cep.9

---

9 The rms error presented in this paper is calculated using the formula: \( \text{rms} = \left( \frac{1}{N} \sum_{i=1}^{N} (y_i - y_{\text{fit}}(\lambda))^2 \right)^{1/2} \), where \( M \) is the number of fitted parameters. This rms error gives an unbiased measure for the quality of the fit, which takes into account the reduced number of free parameters in model 1 compared to model 2.
### Table 5: Polarimetric Parameters of CX Cep from our Multiband Observations

| Parameter | $U$ (%) | $B$ (%) | $V$ (%) | $R$ (%) | $I$ (%) |
|-----------|---------|---------|---------|---------|---------|
| $U_0$ (%) | $5.43 \pm 0.04$ | $6.48 \pm 0.04$ | $6.81 \pm 0.04$ | $6.47 \pm 0.03$ | $5.41 \pm 0.03$ |
| $U_1$ (%) | $-0.04 \pm 0.02$ | $0.07 \pm 0.02$ | $0.07 \pm 0.02$ | $-0.03 \pm 0.01$ | $-0.02 \pm 0.01$ |
| $U_2$ (%) | $-0.12 \pm 0.04$ | $0.09 \pm 0.04$ | $0.06 \pm 0.05$ | $0.11 \pm 0.03$ | $-0.18 \pm 0.03$ |
| $U_3$ (%) | $0.19 \pm 0.05$ | $0.08 \pm 0.04$ | $-0.07 \pm 0.05$ | $0.11 \pm 0.03$ | $0.23 \pm 0.04$ |
| $U_4$ (%) | $0.17 \pm 0.03$ | $0.19 \pm 0.03$ | $0.23 \pm 0.04$ | $0.09 \pm 0.02$ | $0.02 \pm 0.02$ |
| $Q_0$ (%) | $-0.29 \pm 0.04$ | $-0.18 \pm 0.03$ | $-0.42 \pm 0.03$ | $-0.47 \pm 0.03$ | $-0.75 \pm 0.03$ |
| $Q_1$ (%) | $0.03 \pm 0.02$ | $-0.02 \pm 0.02$ | $-0.01 \pm 0.01$ | $-0.09 \pm 0.01$ | $-0.05 \pm 0.01$ |
| $Q_2$ (%) | $0.16 \pm 0.04$ | $-0.07 \pm 0.04$ | $0.09 \pm 0.04$ | $0.01 \pm 0.03$ | $0.03 \pm 0.03$ |
| $Q_3$ (%) | $-0.18 \pm 0.04$ | $-0.38 \pm 0.03$ | $0.00 \pm 0.04$ | $-0.05 \pm 0.03$ | $-0.11 \pm 0.03$ |
| $Q_4$ (%) | $-0.18 \pm 0.03$ | $-0.02 \pm 0.03$ | $-0.20 \pm 0.03$ | $-0.21 \pm 0.02$ | $-0.04 \pm 0.02$ |
| $i$ (deg) | $89 \pm 7$ | $76 \pm 14$ | $86 \pm 9$ | $81 \pm 8$ | $87 \pm 8$ |
| $Q^*( \text{deg})$ | $67 \pm 7$ | $82 \pm 8$ | $65 \pm 7$ | $74 \pm 7$ | $58 \pm 8$ |
| $\tau G$ (%) | $0.10$ | $0.07$ | $0.07$ | $0.08$ | $0.09$ |
| $\tau H$ (%) | $0.36$ | $0.37$ | $0.31$ | $0.24$ | $0.26$ |
| rms$_U$ (%) | $0.16$ | $0.18$ | $0.17$ | $0.09$ | $0.15$ |
| rms$_Q$ (%) | $0.18$ | $0.19$ | $0.18$ | $0.06$ | $0.24$ |

* The errors on $\tau G$ and $\tau H$ were found to be less than 0.02% at the 2 $\sigma$ level, and we decided not to present them explicitly.

* Our definition for $\Omega$ is that of Harries & Howarth (1996).
We can therefore say with certainty that the CIP in not zero and probably very high. However, the resulting interstellar polarization seems very high. According to Serkowski et al. (1975), the maximum interstellar polarization observed for completely aligned dust grains in a purely regular external magnetic field is related to the extinction $E(B - V)$ along the line of sight by the equation $P_{\text{max}} = 9E(B - V)$. Using the absorption $A_V = 3.77$ mag in van der Hucht (2001) and the commonly accepted ratio $R_V = 3.1$ between the extinction and absorption in the $V$ band, we obtain a maximum interstellar polarization along the line of sight toward CX Cep of almost 11%. This is larger than the value determined from model 1 and therefore in accordance with our results, although such a high polarization would necessitate an extreme case of dust-grain alignment. Another source of supporting evidence for this high interstellar polarization is the presence of a normal (i.e., should not show intrinsic polarization) B0.5 V star within 0.11 of CX Cep at a distance of 2.3 kpc (cf. ~6 kpc for CX Cep; van der Hucht et al. 1988) with an average interstellar polarization of 4.5% oriented at an angle of 41$^\circ$ (Heiles 2000). This angle is the same as that determined from model 1 but differs by 10$^\circ$ from the interstellar polarization angle of model 2, therefore supporting the validity of model 1.

The main source of uncertainty on our CIP determination is probably the scarce data coverage centered mainly on phases 0.0 and 0.5, where the scatter is larger (see Fig. 1) due to the presence of blobs in the wind and the alignment of the light sources during eclipses. However, since our multiband observations cover more than three orbits (i.e., 8 nights) and the eclipses were therefore observed at least three times, we believe that any epoch-to-epoch fluctuations were averaged out (i.e., assuming again that the blob distribution follows that of the wind over a long period of time). An estimate of the error caused by the stochastic polarimetric fluctuations can be obtained through the covariance matrix produced by the Levenberg-Marquardt method used to fit and remove the interstellar polarization. The diagonal elements of this matrix are the squared uncertainties on the fitted parameters. These uncertainties depend on the weights (i.e., errors) given to the data points that we assumed to be the rms errors on the BME78 double-wave fits. These rms errors measure the scatter in $Q$ and $U$ caused by blobs (and other non-BME78 behavior) around the mean BME78 curve; thus, they provide an estimate of the maximum vertical shift (i.e., in Stokes $Q$ and $U$) that blobs can impart to our data. Therefore, the covariance matrix provides an upper limit estimate of the error on our fitted CIP. Using this method we obtain a maximum error on the intrinsic polarization of $\sigma_{P_{\text{WR}}}$ = 1%, which is almost 4 times lower than the observed CIP (i.e., $P$ = 3.89%).

Another possibility that we did not consider in the previous two models is a potential wavelength dependence of the CIP like the one reported by Schulte-Ladbeck et al. (1992) in WR 134 and Harries (1995) in WR 137. In these systems, the polarization was found to decrease at longer wavelengths as the thermal continuum radius increases and the Thomson scattering $\tau$ = 1 radius remains constant. Harries & Hilditch (1997) proposed an exponential wavelength dependence for the CIP of the form

$$Q_{\text{WR}}(\lambda) = Q_{\text{WR}}(\lambda_0 - \lambda)/x,$$

$$U_{\text{WR}}(\lambda) = U_{\text{WR}}(\lambda_0 - \lambda)/x,$$

where $\lambda_0$ = 550 nm and $x$ must be determined. Using this function we again fitted the data but relaxed our assumptions regarding the wavelength dependence of the interstellar polarization angle by imposing $C_2 = 0$.

The results of this fit are presented in Table 6 (i.e., model 3) and Figure 5.

Although this third model results in a lower and more common interstellar polarization, the best-fitting $x$-value is large and negative, implying that the CIP sharply increases toward the red instead of decreasing with wavelength as was the case for WR 134 and WR 137. In addition, the functional form for the wavelength dependence of the CIP was chosen arbitrarily, and the good fit obtained could be an artefact of the similar exponential wavelength dependencies for the interstellar polarization and the CIP.

On the basis of these facts, it appears that CX Cep has a very high intrinsic polarization (i.e., $P_{\text{WR}}$ ~ 3%–4%) aligned at 26$^\circ$ from the equatorial plane of reference. This angle does not correspond to either the orientation of the orbital plane (i.e., $\Omega$) or

---

**TABLE 6**

| Parameter | Model 1 | Model 2 | Model 3 | Model 4 |
|-----------|---------|---------|---------|---------|
| $P_{\text{max}}$ (%) | 10.17 | 6.75 | 7.06 | 6.09 |
| $\lambda_{\text{max}}$ (nm) | 545 | 557 | 587 | 554 |
| $C_1$ (deg) | 41 | 51 | 47 | 46 |
| $C_2$ (%) | -31 | -52 | 0$^\circ$ | -58 |
| $U_{\text{WR}}$ (%) | -3.05 | 0$^\circ$ | -0.14 | 0.60 |
| $Q_{\text{WR}}$ (%) | -2.36 | 0$^\circ$ | -0.09 | -1.03 |
| $P_{\text{WR}}$ (%) | 3.89 | 0$^\circ$ | 0.16 | 1.19 |
| $\theta_{\text{WR}}$ (deg) | 26 | N/A | 29 | 165$^\circ$ |
| $\lambda_0$ (nm) | N/A | N/A | 550 | N/A |
| $x$ (nm) | N/A | N/A | -158 | N/A |
| rms (%) | 0.09 | 0.22 | 0.10 | 0.24 |

* Fixed.
the polar axis (i.e., $\Omega + 90^\circ$) of the system. A similar phenomenon was recently observed in the short-period W-R binary CX Cep (Villar-Sbaffi et al. 2005) and indicates an apparent lack of correlation between binarity and wind geometry in WR+O systems. To confirm this assertion, we performed a fit on the constants $Q_0$ and $U_0$ with the constraint $\theta_{WR} = \Omega + 90^\circ$, as would be the case for a tidally distorted wind. The results of this fourth model (i.e., model 4) have an rms error more than twice that of model 1 and confirm the misalignment of the CIP in relation to the orbital axis (see Table 6).

5. DISCUSSION AND CONCLUSIONS

Although it has the second shortest period of all known WR+O binaries in our Galaxy, CX Cep is a relatively poorly studied system. In this paper, we have confirmed the polarimetric orbital parameters determined by other authors and considerably improved their accuracy. The BME78-derived orbital inclination confirmed the almost edge-on configuration of the system and provided an accurate orientation for the line of nodes (i.e., $i = 73^\circ \pm 2^\circ$ and $\Omega = 75^\circ \pm 1^\circ$). However, by including the finite stellar size effects in a model of the polarimetric orbit, we found a lower and more accurate inclination of $65^\circ$. Assuming an error on the orbital inclination of $3^\circ$, the resulting masses for both components can then be found using the orbital solution of Lewis et al. (1993):

$$M_O = \frac{25.2 \pm 1.9 \, M_\odot}{\sin^3 i} = 33.9 \pm 3.6 \, M_\odot,$$

$$M_{WR} = \frac{17.8 \pm 1.4 \, M_\odot}{\sin^3 i} = 23.9 \pm 2.6 \, M_\odot.$$

The mass of the O-star agrees with the spectroscopic masses for Galactic O5–6 V stars (Martins et al. 2005), and the W-R mass falls within the acceptable range for a rotating WNE star with an initial mass of 60 $R_\odot$ (Meynet & Maeder 2003).

Our polarimetric model also allowed us to obtain the mass-loss rate of the W-R component, which was found to lie in the range $(0.3–0.5) \times 10^{-5} \, M_\odot \, yr^{-1}$ and was remarkably independent of the adopted input parameters. However, this value is quite low compared to other WN5 stars with mass-loss rates close to $1 \times 10^{-5} \, M_\odot \, yr^{-1}$. An earlier (i.e., hotter) spectral type (i.e., WN3-4) would be more appropriate for such a low $M$ (Nugas & Lamers 2002). In fact, Lewis et al. (1993) concluded that a WN4 spectral type was also acceptable for the W-R component in CX Cep.

Our most surprising discovery is the presence of a large 3%–4% CIP in CX Cep, higher than that of the most polarized Be stars (Poeckert et al. 1979). Although the uncertainty on this value (and the corresponding high interstellar polarization) is probably high (i.e., up to 1% in the worst case scenario), our analysis shows that the probability that the wind is spherically symmetric is very low. On the basis of the radiative transfer model presented in Harries et al. (1998), this CIP implies an equator-to-pole density ratio higher than 5. Like the W-R binary CQ Cep (Villar-Sbaffi et al. 2005), this departure from spherical symmetry is characterized by a CIP vector misaligned in relation to the natural axes of symmetry of a binary (i.e., the polar and equatorial axes) that points toward a rotational origin for the asymmetry. Alternatively, this could reveal the presence of a magnetic field that is affecting the symmetry of the wind.

Within the observations of Harries et al. (1998) and the models of Meynet & Maeder (2003), CX Cep is an anomaly. Massive stars at solar metallicity should reach the W-R phase with low rotational velocities and therefore spherically symmetric winds. For this reason, the extremely flattened wind of CX Cep should provide valuable information regarding the effects of rotation on massive star evolution and should be studied further.

A. V. S., N. S. L., and A. F. J. M. are grateful for financial support from NSERC (Canada) and FQRNT (Québec). We would also like to thank Andrei Berdyugin for his help operating the NOT telescope and for sharing his observing time with us.

REFERENCES

Bastien, P. 1982, A&AS, 48, 153
Breger, M. 1979, ApJ, 233, 97
Brown, J. C., McLean, I. S., & Emslie, A. G. 1978, A&A, 68, 415
Cassinelli, J. P., & Castor, J. I. 1973, ApJ, 179, 189
Cassinelli, J. P., Nordsieck, K. H., & Murison, M. A. 1987, ApJ, 317, 290
Dolan, J. F., & Tapia, S. 1986, BAAS, 18, 968
Drissen, L., Moffat, A. F. J., Bastien, P., Lamontagne, R., & Tapia, S. 1986, ApJ, 306, 215
Fox, G. K. 1984, ApJ, 432, 262
Gehrels, T., ed. 1974, IAU Colloq. 23, Planets, Stars, and Nebulae: Studied with Photopolarimetry (Tucson: Univ. Arizona Press)
Gliese, W. 1969, Veröff. Astron. Rechen-Inst. Heidelberg, 22, 1
Harries, T. J. 1995, Ph.D. thesis, University College, London
Harries, T. J., & Hilditch, R. W. 1997, MNRAS, 291, 544
Harries, T. J., Hillier, D. J., & Howarth, I. D. 1998, MNRAS, 296, 1072
Harries, T. J., & Howarth, I. D. 1996, A&A, 310, 235
Heiles, C. 2000, AJ, 119, 923
Hsu, J.-C., & Breger, M. 1982, ApJ, 262, 732
Kartasheva, T. A. 2002a, Bull. Spec. Astrophys. Obs., 53, 18
Kartasheva, T. A., Svechnikov, M. A., & Bychkov, V. D. 2000, Bull. Spec. Astrophys. Obs., 50, 51

FIG. 5.—Constant components of the polarization $Q_0$ and $U_0$ as a function wavelength obtained by fitting our NOT observations with a Fourier function up to second harmonics. The solid line represents our fit using a modified Serkowski function plus an additional wavelength-independent term corresponding to the intrinsic polarization of the system. The dashed line represents a fit obtained with an exponential wavelength-dependent CIP (see Harries & Hilditch 1997).
Kurochkin, N. E. 1985, Perem. Zvezdy, 22, 219
Lewis, D., Moffat, A. F. J., Matthews, J. M., Robert, C., & Marchenko, S. V. 1993, ApJ, 405, 312
Lipunova, N. A., & Cherepashchuk, A. M. 1982, AZh, 59, 73
Maeder, A. 1999, A&A, 347, 185
Maeder, A., & Meynet, G. 2000, ARA&A, 38, 143
Martins, F., Schaerer, D., & Hillier, D. J. 2005, A&A, 436, 1049
Matsumura, M., Hamasaka, S., Kikuchi, A., Seki, M., Hirata, R., & Kawabata, K. S. 2003, in Astrophysics of Dust, ed. A. N. Witt (San Francisco: ASP), 6
Meynet, G., & Maeder, A. 2003, A&A, 404, 975
Moffat, A. F. J., & Marchenko, S. V. 1993, AJ, 105, 339
Moffat, A. F. J., & Pirola, V. 1993, ApJ, 413, 724
Nugis, T., & Lamers, H. J. G. L. M. 2002, A&A, 389, 162
Pirola, V. 1977, A&AS, 30, 213
———. 1988, in Polarized Radiation of Circumstellar Origin (Tucson: Univ. Arizona Press), 735
Poockert, R., Bastien, P., & Landstreet, J. D. 1979, AJ, 84, 812
Robert, C., Moffat, A. F. J., Bastien, P., Drissen, L., & St-Louis, N. 1989, ApJ, 347, 1034
Schmidt, G. D., Elston, R., & Lupie, O. L. 1992, AJ, 104, 1563
Schulte-Ladbeck, R. E., Nordsieck, K. H., Taylor, M., Bjorkman, K. S., Magalhaes, A. M., & Wolff, M. J. 1992, ApJ, 387, 347
Schulte-Ladbeck, R. E., & van der Hucht, K. A. 1989, ApJ, 337, 872
Serkowski, K., Mathewson, D. L., & Ford, V. L. 1975, ApJ, 196, 261
St-Louis, N., Moffat, A. F. J., Lapointe, L., Efimov, Y. S., Shakhovskoj, N. M., Fox, G. K., & Pirola, V. 1993, ApJ, 410, 342
van der Hucht, K. A. 2001, NewA Rev., 45, 135
van der Hucht, K. A., Hidayat, B., Admiranto, A. G., Supelli, K. R., & Doom, C. 1988, A&A, 199, 217
Villar-Sbaffi, A., St-Louis, N., Moffat, A. F. J., & Pirola, V. 2005, ApJ, 623, 1092
Whittet, D. C. B., Martin, P. G., Hough, J. H., Rouse, M. F., Bailey, J. A., & Axon, D. J. 1992, ApJ, 386, 562